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Piezoelectric Ceramic Reproducibility (for k_{33}-Mode Transducer Applications)

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A complete solution to the problem of piezoelectric ceramic reproducibility and uniformity has been developed for a certain class of transducers commonly used in fleet sonar (submarine spherical array sonar and surface ship cylindrical array sonar). The solution accommodates the variability of the piezoelectric ceramic elements and assures that the transducers thus produced will meet performance requirements, be electroacoustically interchangeable, and be intermixable with existing units. Included is a Simplified Guidance Model, a new concept in the understanding of 33-mode longitudinal vibrators and the piezoelectric ceramic parameters that control performance. Improved methods of determining ceramic ring and ceramic stack assembly parameters and a noncomputational dynamic test method to certify the performance of a ceramic stack has been developed. The technical solution to the problem of reproducibility has been experimentally validated and data are presented that support the simplified math model.

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CONTENTS

PIEZOELECTRIC CERAMIC REPRODUCIBILITY (FOR k_{33}-MODE TRANSDUCER APPLICATIONS

INTRODUCTION

Piezoelectric ceramic sensors were first introduced into fleet sonar transducers about 30 years ago. The ceramic sensors offered significant advantages in temperature stability, high-power drive capability, high coupling coefficients, low dielectric losses, high dielectric strength, high Curie temperatures, etc. The performance advantages offered by the ceramic sensors were readily accepted and have been exploited over the following years. Unlike their natural crystal predecessors, however, the piezoelectric ceramic elements typically used for the fabrication of high-power longitudinal resonators suffer from the lack of uniformity and reproducibility. Since their first introduction into fleet transducers the Navy has had recurring problems caused by the lack of reproducibility and uniformity of the piezoelectric ceramics. Duplication of a given, desirable sensor element has often proven difficult and, in some cases, impossible. As a result of this and the need to be able to specify the ceramic components for a build-to-print Fabrication Specification Package (FSP), a solution to the problem of reproducibility was developed. The Sonar Transducer Reliability Improvement Program (STRIP), with some assistance from the exploratory development Sonar Transduction Sciences Program, has developed a complete, practical solution to the problem of piezoelectric ceramic reproducibility for a certain class of 33-mode transducer applications.

BACKGROUND

When STRIP first assessed the ceramic reproducibility problem, the following questions were being asked in a spirit of agonizing frustration: Why are sonar transducers not like other normal hardware items that the Navy buys (such as components for engines, radios, radars, guns)? Once the Navy has developed a successful transducer element, why is it not possible in a straightforward, dependable manner to procure more of the same transducer elements? A significant part of the answer to such questions was that neither the Navy nor private industry had developed a practical technical solution to the problem of reproducibility of piezoelectric ceramic components for 33-mode transducer applications. This was true despite the many dollars and man-hours that had been spent on research attempting to solve the reproducibility problem.

When STRIP started its effort to solve the problem the situation was as follows. Each of the major suppliers of piezoelectric ceramic components for transducer elements had spent considerable effort in developing their own proprietary art for reproducing ceramic components. The Navy was often tempted to forego competition in awarding production contracts and, instead, repeatedly procured a given ceramic component from the same vendor. However, many times even this nontechnical solution failed to exactly reproduce the ceramic components, thus resulting in significant delays, costly fix-it programs, or unwanted acceptance of altered transducer performance.

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It is easy to understand that if a given supplier could not reproduce its own ceramic components successfully, then it was even less likely that a different supplier could be expected to reproduce a given component. Nonetheless, in the competitive procurement of the complete transducer elements, to cut costs and have a chance of winning a contract, the bidders were often forced to use different ceramic component suppliers. The fact that the resulting ceramic components would usually be different than those from the original supplier essentially guaranteed that a given transducer could not be reproduced.

Even after STRIP produced and experimentally validated a technical solution to the piezoelectric ceramic reproducibility problem, the STRIP objective had not been met. STRIP was required to translate this technical solution into a practical, dependable set of specifications, acceptance tests, and drawings. In the case of the piezoelectric ceramic components, this meant that STRIP *had to develop and validate specifications that had never been successfully developed before.* The piezoelectric ceramic specifications had to be usable to competitively procure and manufacture additional copies of a given, proven transducer element in a manner fair and practical to both the Government and the winning contractor. The specifications had to be such that the proprietary art of any of the major ceramic suppliers could be successfully applied. STRIP has produced these specifications as required for use in a complete transducer drawing set.

The Naval Research Laboratory normally uses Systems International (SI) units in all reports and scientific articles. This report, however, contains engineering development information and references to NAVSEA drawings where SI units and English units are mixed. Therefore, to maintain continuity with the NAVSEA drawings and practices found among NAVSEA contractors, mixed units are used in this report. English units are restricted to physical dimensions; all other units are SI.

Figures 1 and 2 show a cut-away composite view and an exploded view, respectively, of a typical 33-mode fleet transducer to which the reproducibility solution applies. Note the relationship of the ceramic stack assembly (CSA) to the other components of the transducer in these figures.

PIEZOELECTRIC CERAMIC COMPONENTS

The ceramic piezoelectric components of interest consist of ceramic rings and ceramic stack assemblies. Figure 3 shows a typical piezoelectric ceramic ring, and Fig. 4 shows how a number of rings are formed into a CSA.

The ceramic rings for a typical longitudinal resonator have fired silver electrodes on the two surfaces perpendicular to the longitudinal axis (Fig. 3). When the rings are being manufactured, the rings are polarized by applying a high dc voltage to the electrode surfaces (polarization is analogous to magnetizing a piece of iron to form a permanent magnet). With the rings so polarized, applying a sinusoidal voltage of frequency f to the electrodes causes a sinusoidal motion of f in both the 3 (longitudinal) direction and the 1 (radial) direction. If in the transducer application the motion in the 3 direction is used for rings polarized in the 3 direction, a 33-mode transducer exists. A 31-mode transducer means the ceramic components are polarized and electrically driven in the radial direction, but the motion of the ceramic in the longitudinal direction is used by the transducer. However, for this report only longitudinally polarized ceramic rings operating in the 33-mode are of interest.

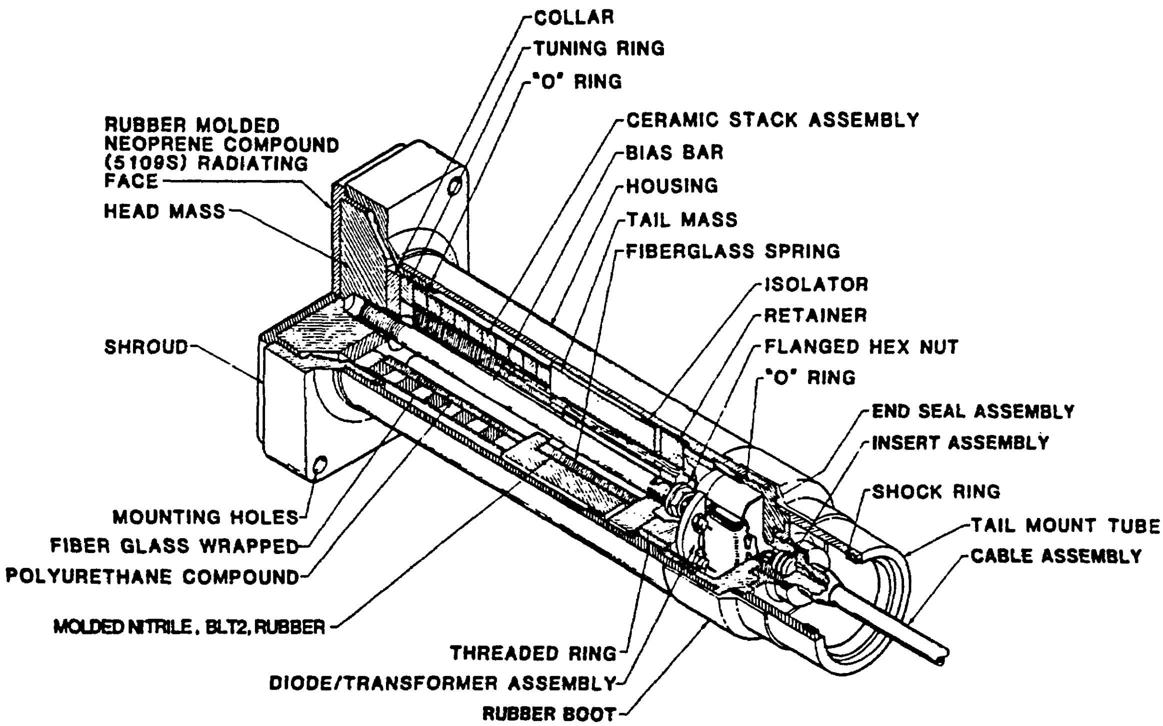

Fig. 1 — Cut-away composite view of a typical 33-mode fleet transducer

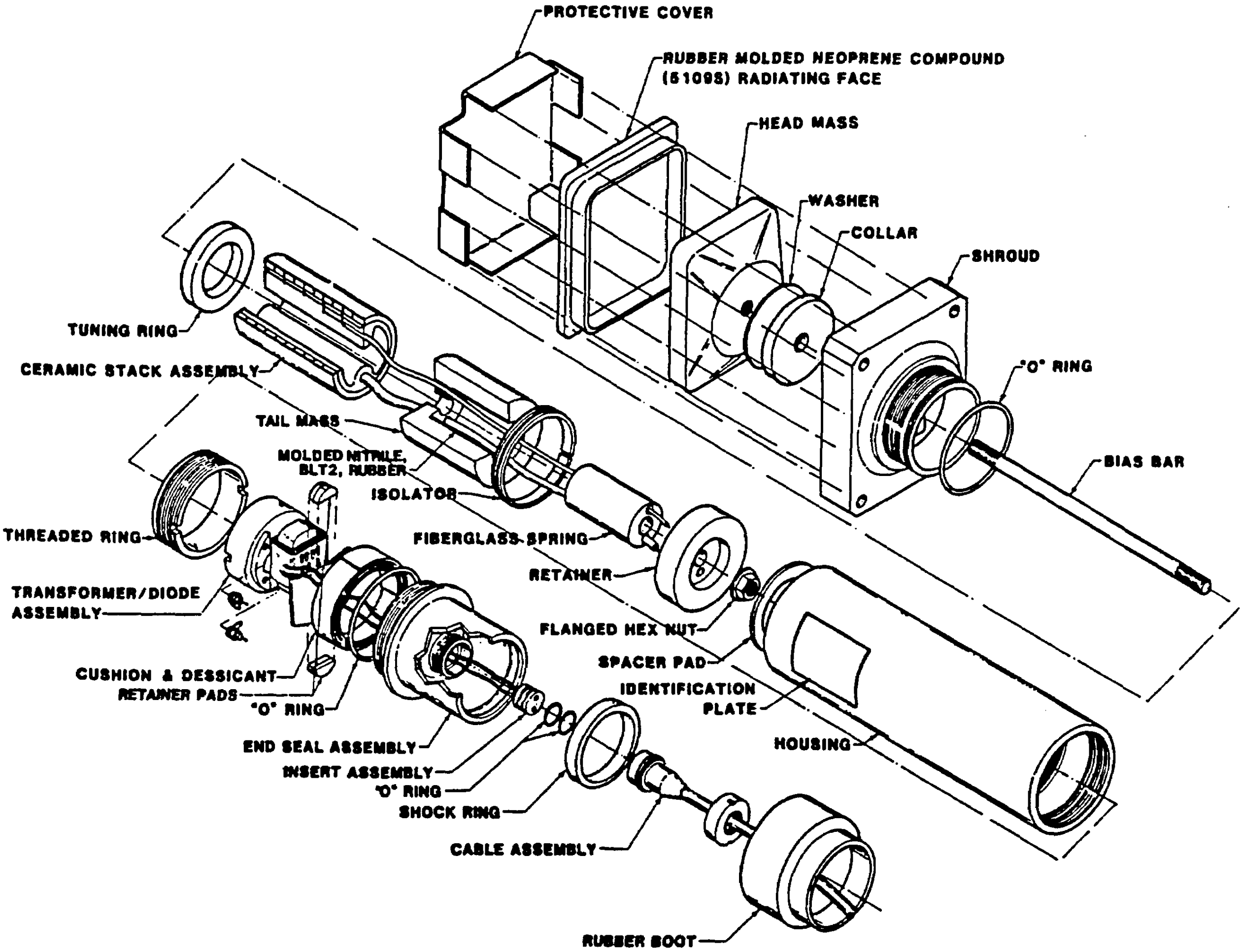

Fig. 2 — Exploded view of a typical 33-mode fleet transducer

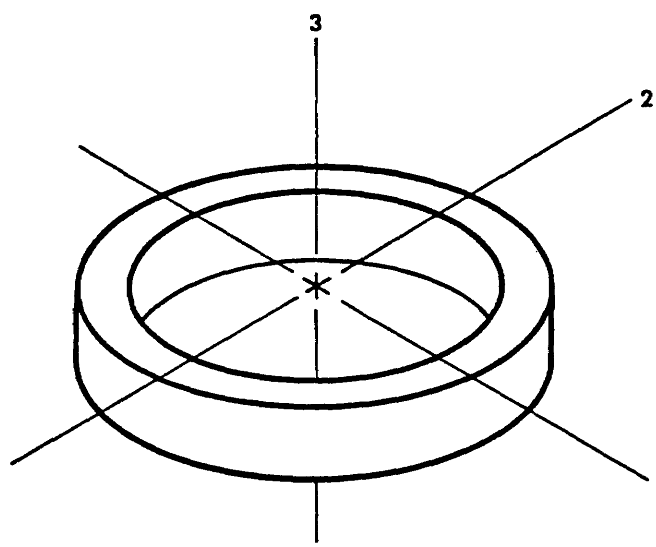

Fig. 3 — Typical 33-mode piezoelectric ceramic ring

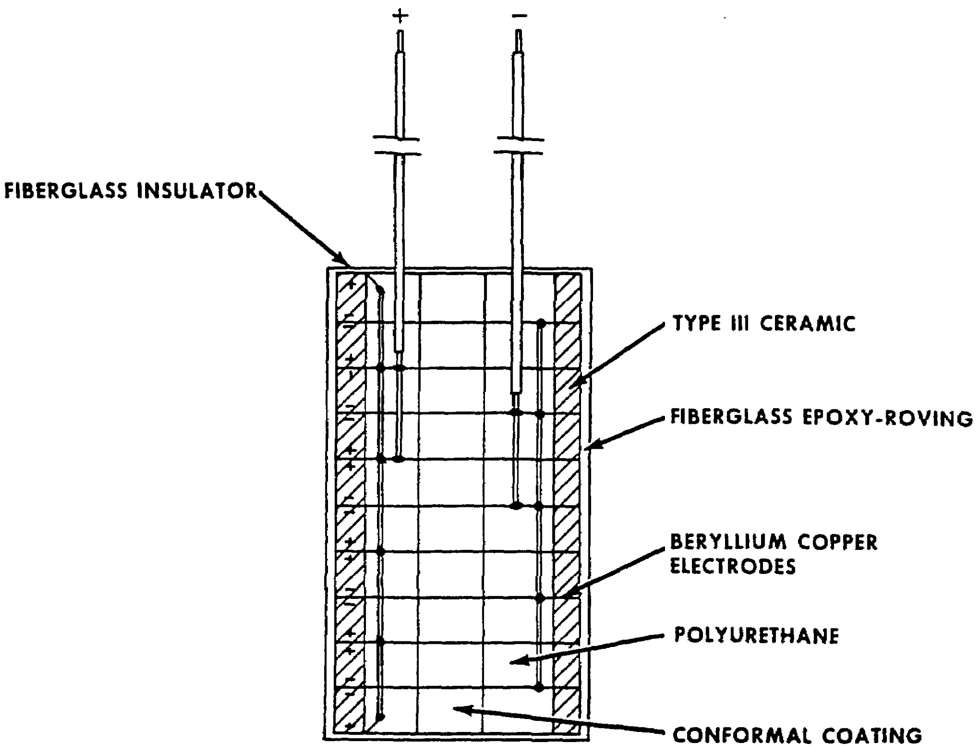

Fig. 4 — Ceramic Stack Assembly (CSA)

In the typical 33-mode transducer (shown in simplified form in Fig. 5) the CSA is prestressed in both the radial/circumferential and longitudinal direction to permit high-power drive and also to allow the transducer to meet explosive shock requirements. The radial/circumferential prestress is achieved by using a fiberglass-wrapped CSA (impregnated with an epoxy) (Fig. 4) and the longitudinal prestress (Fig. 5) is achieved by using a steel bias bar (also called a tie rod or stress rod). Although such a CSA is three-dimensionally stressed—since the radial/circumferential stress is applied simultaneously by the fiberglass-wrap process and the longitudinal stress by a bias rod—the stack, so stressed, will be referred to as a doubly stressed stack. Under such conditions each type of applied stress alters the piezoelectric, dielectric, and elastic parameters of the CSA. However, the parameter changes resulting from the radial/circumferential stress tend to be opposite to those resulting from the longitudinal stress. Therefore, when all stresses are applied simultaneously, the overall change in the parameters of the doubly stressed stack is less than if either stress were applied separately.

TECHNICAL PROBLEMS

This section describes in detail the overall technical problems that had to be solved.

Development of 33-Mode Ceramic Ring Specification

In previous applications, even though a 33-mode transducer application was being used, typically a 31-mode ring specification was being applied. This was true simply because the 31 (or radial) mode for rings was thought to be easier to measure and interpret than the 33 mode for rings. Figure 6 shows a typical plot of admittance vs frequency for a ring electrically driven in air (carefully

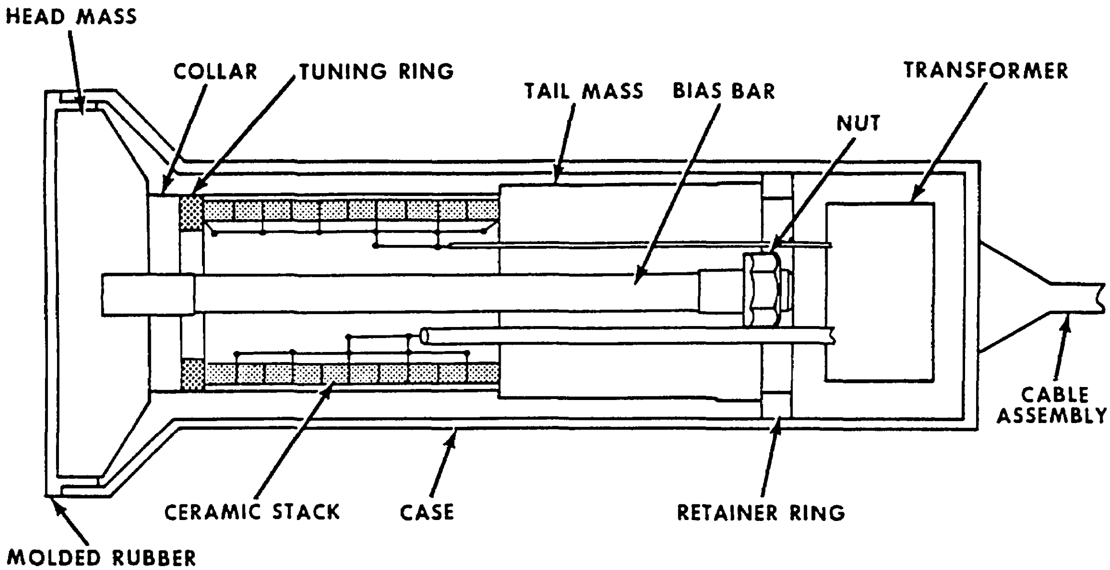

Fig. 5 — Simplified form of a typical 33-mode transducer

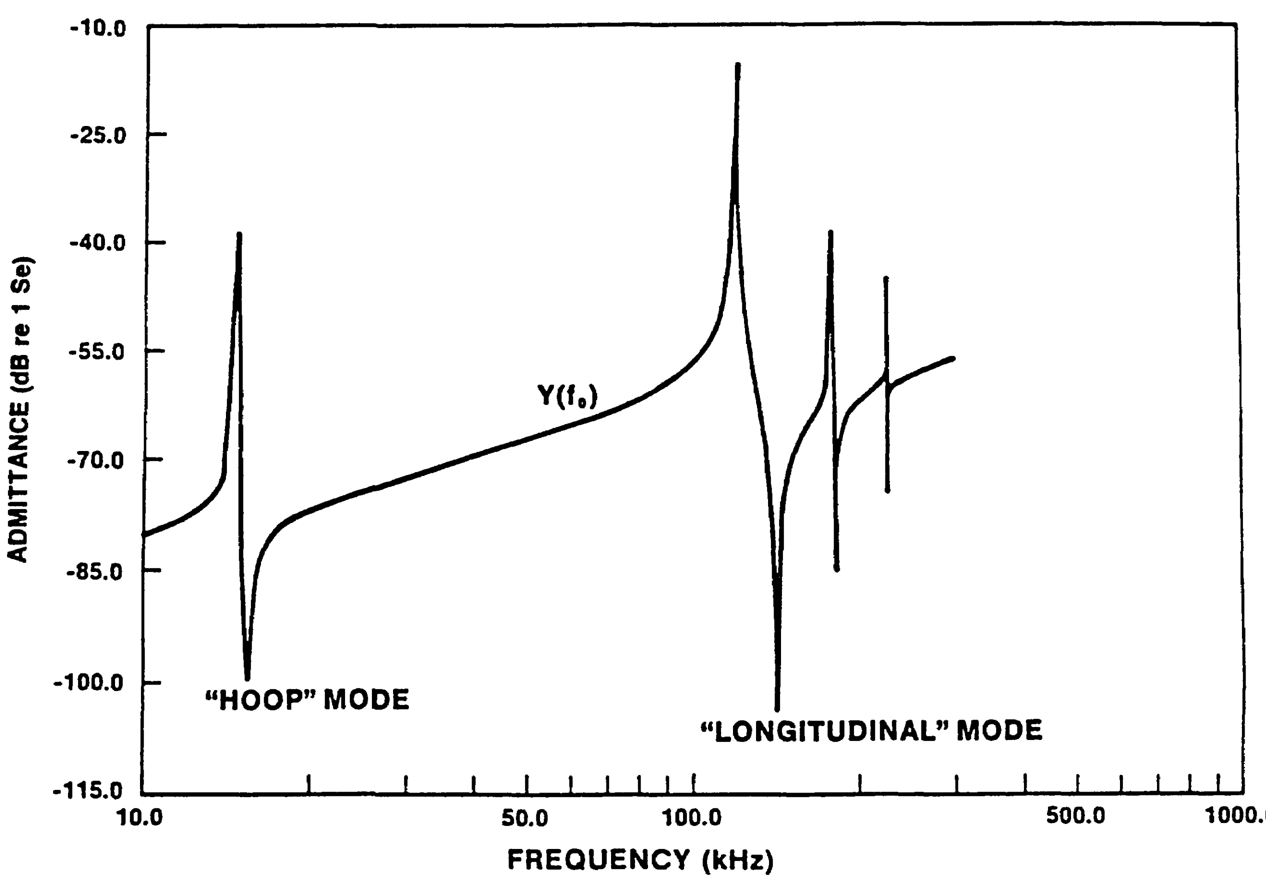

Fig. 6 — Admittance vs frequency of piezoelectric ceramic ring electrically driven in-air

suspended). The lower resonance is primarily associated with the 31, or hoop, mode, and the next higher resonance is primarily associated with the 33 mode (sometimes referred to as the thickness or longitudinal mode). However, depending on the relative dimensions of the longitudinal thickness vs the outside diameter (o.d.) and the inside diameter (i.d.) of the ring, these two modes and other modes are more or less tightly coupled (not independent).

A ring manufacturer could produce rings that met a 31-mode ring specification, but these did not necessarily result in CSAs that met the transducer performance requirements; sometimes they did and sometimes they did not. Because a 31-mode ring specification did not guarantee reproduction of 33-mode CSAs, it was decided that the technology should be developed so that a 33-mode ring specification could be produced and used in conjunction with 33-mode CSAs and transducers.

Ring Mode Coupling Problem

One obstacle in producing a 33-mode ring specification was that unknown errors were introduced by coupling to the 31 and other modes. The coupling problem was solved in part by developing a mathematical model that accounted for the modal coupling; the model with its associated technique was named the Modal Decoupling Resonant Method for ring parameter determination [1,2]. The STRIP solution to the mode coupling problem is described in the section SOLUTION TO THE TECHNICAL PROBLEMS.

Ceramic Ring to Ceramic Stack Assembly Relation Question

Even if a satisfactory 33-mode ring specification could be produced, the question remained of the relation between 33-mode ring parameters and the 33-mode parameters of the corresponding doubly stressed CSA. Specifically, the question was: If one produces rings that meet the STRIP-developed 33-mode ring specification requirements, does this guarantee that these rings will produce doubly stressed CSAs that meet all the transducer performance requirements? As is shown in subsequent sections of this report, very demanding experiments have been performed that strongly indicate that the answer is yes. This means that if the rings meet the new STRIP 33-mode ring specification, then CSAs produced by using these rings will automatically meet the transducer requirements. The next subsection describes a further test that guarantees, early in the production cycle, that the rings being produced will be satisfactory for use in the transducers.

CSA Dynamic Test and Corresponding Specification

For at least two reasons it was decided that the FSP must include not only a 33-mode ceramic ring specification but also a 33-mode CSA Dynamic Test Specification (CDYT). The first reason was that in the event a composite transducer element fails to meet the FSP performance requirements then some means must be available to determine if the FSP is at fault or if the manufacturer made an error. Thus, a separate valid performance test was needed as part of the FSP for the CSA.

The second reason was, since STRIP did not develop absolute proof that rings meeting the STRIP 33-mode ceramic ring specification would produce satisfactory doubly stressed CSAs, then the FSP must have an early test of the rings as they manifest themselves in doubly stressed CSAs. This test is provided by the CSA Dynamic Test Specification. As yet, even in radical cases, no rings that meet the 33-mode ring requirements have failed to meet the corresponding doubly stressed CSA requirements. If they did, this would be detected before any rings were accepted, and the ring supplier would iteratively adjust the controllable processes until the rings did meet CSA requirements.

SOLUTION TO THE TECHNICAL PROBLEMS

This section gives the solution to the piezoelectric ceramic reproducibility problem for 33-mode transducer application. The solution is complete in that it includes the theory, experimental verification, specifications, and tests required by an FSP.

The details of the individual steps in achieving the solution may be more easily presented if the technical heart or kernel of the solution that was developed is first described. For continuity with the STRIP quarterly progress reports, it is noted that in these reports this kernel of the solution was called Design Adjustment Scheme No. 7 (DAS-7) [3,4]. The name DAS-7 is therefore used in the remainder of the present report.

Design Adjustment Scheme (DAS-7)

To completely reproduce a given doubly stressed CSA with no design adjustments, the manufacturer must simultaneously reproduce three independent CSA parameters (a piezoelectric, a dielectric, and an elastic). Because reproducing all three parameters proved difficult and at times impossible in the past, the ceramic suppliers were questioned to determine if they felt confident in reproducing at least one parameter. The answer was that reproducing any one of the three parameters should be easy if the other two were allowed to vary a little. Therefore, at this point, the problem for STRIP was to decide which two of the three parameters could be allowed to vary and be most easily accommodated by using transducer design adjustments, and which one parameter should be required not to deviate from baseline and for which there would be no transducer design adjustments.

The end result was that if the ceramic vendor could duplicate only one of the three ceramic parameters, then this should be the piezoelectric constant d_{33}. Actually, it is important to note that it is the d_{33} for the doubly stressed CSA, as opposed to individual rings, that needs to be reproduced. If the baseline value for the original doubly stressed CSA is denoted as $d_{33_{sb}}$ then in equation form the ceramic supplier must make

$$d_{33_s} = d_{33_{sb}}. \tag{1}$$

In this report the subscript b indicates the baseline value of the given quantity, and the subscript s indicates a doubly stressed CSA quantity as opposed to a ceramic ring quantity. Thus, the quantity d_{33_s} applies to CSAs, and d_{33} applies to ceramic rings.

The piezoelectric constant d_{33} is defined as the longitudinal strain/electric field for a constant applied stress denoted in meters/volts (m/V).

The other two parameters in the adjustable form that the supplier must achieve are the low-frequency capacitance C_{T_s} (a dielectric parameter) and the 33-mode open-circuit compliance C'_{cs} (an elastic parameter) denoted in meters/newtons (m/N) . (The short circuit compliance C_{cs} would be equally satisfactory.) If the baseline transducer has been properly engineered for reproducibility, for practical purposes any reasonable value of C'_{cs} can be accommodated by correspondingly adjusting the thickness of the fiberglass tuning ring (FTR) shown in Fig. 5 (Note: the tuning ring can be located at either the tail or head end of the CSA.) Thus, producing a satisfactory value for C'_{cs} is generally not a difficult restriction on the ceramic ring supplier.

The formula for the low-frequency capacitance of a ring is given by

$$C_T = \frac{\epsilon_{33}^T A}{\ell}, \tag{2}$$

where

- A is the area of ceramic ring (either one of the foiled areas of the ceramic ring (Fig. 3),
- ℓ is the thickness of ceramic ring (Fig. 3), and
- ϵ_{33}^T is the low-frequency dielectric constant, where $\epsilon_{33}^T = K_{33}^T \epsilon_o$, K_{33}^T is the relative dielectric constant of the material, and ϵ_o is the permittivity of free space 8.8542×10^{-12} Farads/meter (F/m).

The low-frequency capacitance of the doubly stressed CSA, C_{Ts}, has the same form but must consider that N rings are wired in parallel. Thus C_{Ts} is given by

$$C_{Ts} = \frac{N \epsilon_{33s}^T A}{\ell}. \tag{3}$$

If the ceramic supplier can, in addition to d_{33s}, duplicate a second parameter then Eq. (4) must be complied with:

$$\epsilon_{33s}^T = \epsilon_{33sb}^T. \tag{4}$$

If the ceramic supplier cannot comply with Eq. (4), the area A can be adjusted, or if the specification allows, the thickness ℓ can be adjusted such that

$$C_{Ts} = C_{Tsb}. \tag{5}$$

Summary of the DAS-7 Three-Step Procedure

DAS-7 is a three-step procedure performed on the CSA and FTR.

1. Adjust d_{33s} of the CSA so that $d_{33s} = d_{33sb}$.

   Note: d_{33} is adjusted by the ceramic manufacturer by varying such quantities as composition of the ceramic material and thoroughness of poling.

2. Adjust low-frequency capacitance C_{Ts} of the CSA so the $C_{Ts} = C_{Tsb}$.

   Note: If the manufacturer is unable to adjust C_{Ts} and d_{33s} simultaneously by using material processes, C_{Ts} may be adjusted by adjusting ceramic ring area A and/or ring length ℓ (see Eq. (3)).

3. Adjust FTR compliance (C_F) so that either:

   (a) $C'_{cs} + C_F = C'_{csb} + C_{Fb}$ (matching f_{ns}), or
   (b) $C_{cs} + C_F = C_{csb} + C_{Fb}$ (matching f_{ms}).

   Note: Adjust the compliance by adjusting the thickness and/or area of the FTR. If an FTR does not exist for a given CSA, a DAS-7 cannot be completed for that CSA.

If the above three steps of DAS-7 are achieved for a given CSA and FTR, these components can be substituted in the original baseline transducer without altering the electroacoustic performance. The longitudinal vibrator must be such that the simplifying assumptions described below in the Simplified Guidance Model (SGM) section of this report are applicable. However, for all high power, low- to mid-frequency fleet transducers considered in STRIP, these simplifying assumptions proved to be highly applicable.

If the ring thickness ℓ were changed from baseline value in step 2, then the electric field ξ would be different from baseline value by

$$\xi = \xi_b \ell_b / \ell. \tag{6}$$

However, if only ceramic area were adjusted in step 2, then the electric field would be equal to the baseline value. For this last reason, and to not affect the overall length of an existing transducer, the STRIP FSPs allow only a ceramic ring area adjustment.

No adjustment of inductance or transformer turns ratio is required by DAS-7.

Major Steps in Achieving the Solution

Achieving the complete solution to the piezoelectric ceramic reproducibility problem for 33-mode applications required a number of varied results. The complicated computerized predictive models had to be augmented by what has been called a Simplified Guidance Model (SGM) to understand the technical heart or kernel of the solution and to communicate with both the ceramic suppliers and the transducer engineers. Existing methods of measuring 33-mode ring parameters, especially d_{33}, had to be improved and, later for production purposes, simplified. In a comprehensive, convincing manner, all the developmental results had to be translated into specifications and corresponding practical, definitive, dynamic tests. All the theory and practice had to be experimentally verified for the participants to have the confidence to apply the solution to important Navy transducer element procurements. Finally, the FSP specifications, tests, and drawings had to be perfected from a practical production point of view.

Simplified Guidance Model (SGM)

Up to a certain point in the effort to produce a solution to the piezoelectric ceramic reproducibility problem, STRIP was relying on extensive tabular and graphic displays of computer-generated data to determine what parameters were most important and what adjustments were possible and practical. Many things were learned from these computer-aided calculations including evidence that a SGM might exist. However, it was not until the SGM was developed that the kernel of the solution was deduced and the full implications clearly understood. The SGM has proven useful and at times necessary in the following ways:

- The SGM provides simple relations between material and geometric parameters and overall performance measures such as resonance frequency and source level. These simple relations aid in understanding the essentials of the problem and can aid in the efficient use of the more exact models.

- By identifying which parameters or groups of parameters are important to control, the SGM aids in the communication between the customer, the transducer engineer, and the ceramic vendor.

- The SGM suggests changes that can be made in other transducer design parameters to compensate for the difficulty of exact reproduction of a given baseline ceramic ring and CSA. These changes are referred to as design adjustments.

Figure 5 shows the general form of the longitudinal vibrator transducer for which the SGM was derived. In the SGM as applied to the CSA reproducibility problem, the only components that are allowed to change are

- ceramic rings—material properties and dimensions;

- fiberglass tuning ring—material properties and dimensions; and

- external electrical components such as capacitors, inductors and transformers.

All other transducer components are assumed to be unchangeable or fixed.

The five main simplifying assumptions used in the derivation of the SGM are:

1. The CSA is sufficiently short in wavelengths so that

$$\tan\left(\frac{\omega\, L_s}{C_e}\right) \approx \frac{\omega\, L_s}{2\, C_e}, \tag{7}$$

and

$$\sin\left(\frac{\omega\, L_s}{C_e}\right) = \frac{\omega\, L_s}{C_e}, \tag{8}$$

where

L_s is total length of CSA
C_e is sound speed in ceramic corresponding to a constant electric field, and
ω = 2π (frequency).

2. The primary resonance frequency of the unloaded CSA is much higher than the operating frequency band of the composite longitudinal vibrator. (Thus the mass of the ceramic stack is ignored in the SGM).

3. The stress rod is sufficiently compliant relative to the compliance of the CSA that it can be neglected in the SGM.

4. The material losses in the CSA are negligible compared to other loss mechanisms in the transducer.

5. The FTR is short enough in wave lengths that it can be represented by a pure massless compliance C_F.

These approximation assumptions have proven highly applicable for all high-power, low- to mid-frequency transducers considered in STRIP tasks.

A derivation and discussion of the SGM is presented in Refs. 5-7. One key result of the SGM development is

$$\begin{pmatrix} E \\ \\ I \end{pmatrix} \quad \begin{bmatrix} \frac{1}{N\, d_{33}} (C_F + C_{cs}) & \frac{1}{i\omega\, N\, d_{33s}} \\ \\ i\omega \frac{A}{g_{33}\ell} (C_F + C_{cs}') & \frac{A}{g_{33}\ell} \end{bmatrix} \quad \begin{pmatrix} F \\ \\ V \end{pmatrix} \tag{9}$$

The new symbols introduced in matrix Eq. (9) are defined as

g_{33} is piezoelectric constraint, relating charge density to displacement;
F is a force to be implicitly defined below;
V is a velocity to be defined further below;
E is voltage applied to the CSA; and
I is current into the CSA.

Equation (9) is a key relation and was used extensively in the development of the SGM, some of which follows.

Since $F = ZV$, it follows from Eq. (9) that

$$\frac{E}{V} = \frac{1}{Nd_{33s}} (C_F + C_{cs}) Z + \frac{1}{i\omega d_{33s}} ,$$

and

$$\frac{I}{V} = i\omega \frac{A}{g_{33s}\ell} (C_F + C_{cs}') Z + \frac{A}{g_{33s}\ell} . \tag{10}$$

Inverting Eqs. (10) and (11):

$$\frac{V}{E} = \frac{i\omega\, N\, d_{33s}}{1 + i\omega\, (C_F + C_{cs}')Z} \tag{12}$$

$$\frac{V}{I} = \frac{g_{33s}\ell}{A} \frac{1}{1 + i\omega\,(C_F + C'_{cs})Z}. \tag{13}$$

For the development of the SGM, Ref. 7 shows that

$$V_T = \frac{Z_H\, V_H}{Z_T}. \tag{14}$$

The new symbols introduced in Eq. (14) are defined as:

V_T is velocity at the tail end of the ceramic;
V_H is velocity at the head end of the fiberglass washer;
Z_H is combined impedance of the head assembly and acoustic load; and
Z_T is the tail mass assembly impedance.

Results from the development of the SGM model and Eq. (14) yield

$$V = V_H - V_T = \left(1 + Z_H/Z_T\right) V_H. \tag{15}$$

One important measure of transducer performance is source level. Source level (not in dB) is proportional to V_H at each frequency, and the constant of proportionality depends only on the frequency, the nature of the head assembly, and the properties of the acoustic medium. It follows from Eq. (15) that V also is proportional to source level, and the constant of proportionality does not depend on any of the quantities that are being allowed to change.

For this report, the quantities V/E and V/I are equivalent to source level/volt and source level/ampere as measures of transducer performance. Equation (12) clearly shows that source level/volt is determined by N, d_{33}, and $C_F + C_{cs}$. Similarly, Eq. (13) shows that source level/ampere is determined by $g_{33s}\,\ell/A$ and $(C_F + C'_{cs})$.

Let Z_a denote the value of Z when the longitudinal vibrator is operating in air. If material losses in the head assembly are neglected, the quantity Z_a will be purely imaginary, i.e.,

$$Z_a = i\ [\text{Imag. part of } Z_a] \equiv i\ \text{Im}\,(Z_a). \tag{16}$$

Substituting Eq. (16) into Eqs. (12) and (13) gives

$$\frac{V}{E}\Big|_{\text{in-air}} = \frac{i\omega\, N\, d_{33s}}{1 - \omega\,(C_F + C_{cs})\,\text{Im}\,(Z_a)} \tag{17}$$

and

$$\frac{V}{I}\Big|_{\text{in-air}} = \frac{g_{33s}\ell}{A} \frac{1}{1 - \omega\,(C_F + C'_{cs})\,\text{Im}\,(Z_a)}. \tag{18}$$

Equations (17) and (18) show that V/E in-air is determined by N, d_{33s}, and $(C_F + C_{cs})$ and V/I in air is determined by $g_{33s}\, \ell/A$ and $(C_F + C'_{cs})$: This is similar to the in-water results.

If Eq. (17) is divided by Eq. (18), the in-air admittance Y_a can be written as

$$Y_a = \frac{i\,\omega\, N\, d_{33s}}{\dfrac{g_{33s}\,\ell}{A}} \, \frac{1 - \omega\,(C_F + C'_{cs})\,\mathrm{Im}\,(Z_a)}{1 - \omega\,(C_F + C_{cs})\,\mathrm{Im}\,(Z_a)} . \tag{19}$$

It follows from Eq. (19) that the in-air resonance ω_m occurs when

$$C_F + C_{cs} = \frac{1}{\omega_m\,\mathrm{Im}\,[Z_a\ (\text{at } \omega_m)]}, \tag{20}$$

and the in-air antiresonance occurs when

$$C_F = C'_{cs} = \frac{1}{\omega_n\,\mathrm{Im}\,[Z_a\ (\text{at } \omega_n)]} . \tag{21}$$

Thus, the in-air resonance is determined by $(C_F + C_{cs})$ and the in-air antiresonance is determined by $(C_F + C'_{cs}.)$

Suppose that it is desired to build a longitudinal vibrator having the same performance as a prescribed "baseline" unit by using ceramic having different parameters than those of the baseline unit. We now show that certain other design parameters can be adjusted to compensate for the difference in ceramic parameters.

The first thing to notice is that if the transfer matrix in Eq. (9) can be made the same as the baseline transfer matrix, then the performance of the longitudinal vibrator will be the same as with the baseline unit. The matrix in Eq. (9) can be factored as:

$$\begin{bmatrix} \dfrac{1}{N\,d_{33s}} & (C_F + C_{cs}) & \dfrac{1}{i\omega\,N\,d_{33s}} \\ \\ i\omega\,\dfrac{A}{g_{33s}\,\ell} & (C_F + C'_{cs}) & \dfrac{A}{g_{33s}\,\ell} \end{bmatrix} = T_1\, T_2, \tag{22}$$

where

$$T_1 = \begin{bmatrix} \dfrac{1}{N\,d_{33s}} & 0 \\ \\ 0 & N\,d_{33s} \end{bmatrix}, \tag{23}$$

and

$$T_2 = \begin{bmatrix} C_F + C_{cs} & & \dfrac{1}{i\omega} \\ i\omega \dfrac{A}{d_{33s}\, g_{33s}\, L_s} & (C_F + C'_{cs}) & \dfrac{A}{d_{33s}\, g_{33s}\, L_s} \end{bmatrix} \tag{24}$$

The quantity $A/(d_{33s}\, g_{33s}\, L_s)$ in T_2 can be made the same as in baseline unit by adjusting the ratio A/L_s. Once A/L_s has been determined, the quantity $C_F + C_{cs}$ in T_2 can be made the same as baseline by adjusting the compliance C_F of the FTR, provided $C_{cs} < (C_F + C_{cs})$ baseline. For example, the compliance C_F can be changed by changing the length of the FTR. It follows from Eqs. (11), (18), and (21) that

$$C_F + C'_{cs} = C_F + \frac{S^D_{33s}\, L_s}{A} = C_F + \frac{S^E_{33s}\, L_s}{A} - \frac{g_{33s}\, d_{33s}\, L_s}{A}$$

$$= C_F + C_{cs} - \frac{g_{33s}\, d_{33s}\, L_s}{A}, \tag{25}$$

therefore making $(C_F + C_{cs})$ and $A/(g_{33s}\, d_{33s}\, L_s)$ the same as baseline forces $(C_F + C'_{cs})$ to be the same as baseline. Hence, it has been shown that the matrix T_2 can be made the same as the corresponding baseline matrix by adjusting C_F and A/L_s. An alternative approach for making T_2 the same as baseline would be to choose C_F so that $(C_F + C'_{cs})$ is the same as baseline. This together with the requirement that $A/g_{33}\, d_{33s}\, L_s)$ is the same as baseline forces $(C_F + C_{cs})$ to be the same as baseline.

The matrix T_1 has the same form as the transfer matrix of an ideal transformer. Thus, T_1 can be made the same as baseline by an external transformer. This completes the demonstration that both T_1 and T_2 can be made the same as the corresponding baseline matrices.

In some cases it is not practical to use an external transformer to make design adjustments. For example, for the transducers considered in STRIP, a diode switch removes the transformer from the circuit during receive. The definition of T_1 in Eq. (23) clearly shows that *an adjustment of the external transformer is not necessary if the ceramic vendor can control* d_{33s} *to make it the same as the baseline value*. If d_{33s} is the same as in the baseline unit, then the requirement that $A/(g_{33}\, d_{33}\, L_s)$ in T_2 be made the same as baseline is equivalent to the requirement that the low-frequency capacitance C_{Ts} be made the same as baseline. This can be seen as follows:

$$\frac{A}{g_{33s}\, d_{33s}\, L_s} = \frac{A}{\left(\dfrac{d_{33s}}{\epsilon^T_{33s}}\right) d_{33}\, L_s} = \frac{\left(\dfrac{\epsilon^T_{33s}\, A}{\ell}\right)}{N\, d^2_{33s}} = \frac{C_{Ts}}{N^2\, d^2_{33s}}, \tag{26}$$

where

$$C_{Ts} = N\left[\frac{\epsilon_{33s}^{T} A}{\ell}\right] \tag{27}$$

This particular design adjustment involving d_{33_s} and C_{Ts} was discussed earlier where it was called Design Adjustment Scheme No. 7 (DAS-7).

PARAMETER DETERMINATION

DAS-7 would not be very useful if the parameters that had to be adjusted could not be at least indirectly measured. You should be able to determine when and if the correct values of d_{33}, C_{Ts}, and C'_{cs} were achieved. The CSA and ring ceramic parameter measurement issues are discussed in this section. But, again it must be emphasized that DAS-7 is directly concerned only with the transducer CSA parameters as opposed to the parameters of the ceramic rings used to construct the given CSA. Furthermore, DAS-7 is concerned with the CSA parameters for the appropriate environmental conditions (such as prestress, temperature, depth). In the transducers to which DAS-7 has been applied, the CSA was subject to both a radial/circumferential prestress (fiberglass wrapped) and a longitudinal prestress (applied by using a stress rod). This condition has been referred to as a doubly stressed CSA. However, the ceramic ring vendor must work with ceramic ring parameters, and it is a separate issue as to whether or not achieving baseline ring values for d_{33} and C_T (with some attention to ring compliance) will always result in baseline values for a corresponding doubly stressed CSA. For even the most radical departures from baseline ceramic formulations tested thus far, this has turned out to be the case. This ring-to-CSA parameter issue is discussed further in the section EXPERIMENTAL VALIDATION OF THE STRIP SOLUTION.

CSA Parameters

The standard method of determining the doubly stressed CSA parameters is to use impedance and resonance measurements on a longitudinally stressed mass-loaded CSA (dumbbell) and apply a standard computerized routine. However, the in-air SGM results can be used to show that a simplified technique involving no computations can be used to determine indirectly whether or not all the correct DAS-7 CSA parameters (d_{33_s}, C_{Ts}, and C'_{cs}) have been achieved.

The noncomputational method to determine whether the correct DAS-7 parameters have been achieved is described next. Instead of a dumbbell apparatus, the corresponding parts of the actual transducer are used as a test device. Specifically, the test device uses the head mass, tail mass, and stress rod (as shown in Fig. 5) and excludes all other transducer components, especially any lossy components such as rubber mounts. This device is referred to as the CSA dynamic tester (CDYT). Installing the CSA to be tested in representative transducer components (the CDYT) helps ensure that boundary conditions of the actual transducer are applied to the CSA. This includes the prestress conditions.

First, the CSA to be tested, together with an initial selection of FTR, is installed in the CDYT at the proper prestress. Second, the value of C_{Ts} of the CSA installed in the CDYT is measured in the conventional manner. Third, if C_{Ts} is found to be correct, $|Z_{\text{in}}|$ can be measured and plotted to determine if the proper thickness of FTR had been selected. If not, the FTR can be iteratively adjusted until f_n (or alternately f_m) occurs at the proper frequency. Fourth, once the FTR is adjusted to produce the baseline value of f_n then one can check to see if the baseline value f_m has automatically been achieved. (If f_m has been adjusted to the baseline value, one can see if f_n has automatically been adjusted to the baseline value).

Thus, confirmation that DAS-7 parameters (d_{33s}, C_{Ts}, and those concerning compliance) have been achieved (within certain tolerances) consists of noting three items:

1. $C_{Ts} = C_{Tsb}$

2. A FTR existed so that $f_n = f_{nb}$ (or alternately, one could adjust $f_m = f_{mb}$).

3. $f_m = f_{mb}$ is automatically achieved (or alternately, $f_n = f_{nb}$ is automatically achieved if the adjustment of item 2 were performed on f_m).

The basis for asserting that achieving the above three conditions is equivalent to proving that the DAS-7 parameters meet specifications is essentially the same as the basis for DAS-7 proper. To see this, first note that the DAS-7 parameter C_T is measured directly and is shown to be equal to C_{Tsb} as specified. Next, according to Eq. (21), $f_n = f_{nb}$ (note: $f_n = \omega_n/2\pi$) can occur if and only if the composite compliance ($C_F + C_c'$) has been adjusted (by using the FTR) to be equal to the specified baseline value. Lastly, after having achieved $C_{Ts} = C_{Tsb}$ and ($C_F + C_{cs}'$) equal to the baseline value, then $f_m = f_{mb}$ occurs if and only if $d_{33} = d_{33b}$ as required to satisfy DAS-7.

This last assertion can be shown to be true by using Eqs. (20), (25), and (26). Equation (20) shows that $f_n = f_{nb}$ if and only if ($C_F + C_{cs}$) is equal to the baseline value. Equations (25) and (26) considered together show that with $C_{Ts} = C_{Tsb}$ and ($C_F + C_{cs}'$) equal to the baseline value then, indeed, $f_m = f_{mb}$ if and only if $d_{33} = d_{33b}$. This chain of reasoning completes the demonstration that a CSA satisfies the listed conditions for the CDYT if and only if the required three DAS-7 parameters have been achieved by this CSA.

As a further but redundant direct check that $d_{33} = d_{33b}$, V/E could be measured and plotted in air.

Appendix A provides an actual example of the CSA Dynamic Test Specification using the above-described CDYT for the TR-330A transducer.

Ceramic Ring Parameter Determination

The ceramic vendor works directly with ceramic ring parameters—not the doubly stressed stack parameters. However, it was decided that the ceramic ring vendor should follow the first two steps of the three-step DAS-7 procedure, except as applied to rings, not to CSAs. Specifically, this meant that the ceramic manufacturer must first force d_{33} of the new rings to be equal to the ring baseline value d_{33b} (within certain tolerances). (Recall that when no subscript s is on a quantity this indicates a ring quantity, not a CSA quantity.) Next, using an area adjustment if necessary, the low-frequency capacitance of the ring C_T must be made equal (within allowed tolerances) to the baseline ring value C_{Tb}. For rings, in summary:

Step 1. $d_{33} = d_{33b}$

Step 2. $C_T = C_{Tb}$ (adjust A if necessary).

Only very loose tolerances were put on C_c' for the rings because the compliance for the resulting CSAs was to be accommodated by using a properly chosen FTR. However, some restrictions must be placed on C_c' and this is noted as:

Step 3. $C_c' \approx C_{cb}'$

Measuring C_T for rings was not and is not a problem. Measuring d_{33} for the rings was a problem. Different laboratories and private companies reported erratic results when using the Berlincourt d_{33} meter to measure large ceramic rings. Cutting the rings into long thin rods to eliminate modal coupling was not permissible. This was because each ring had to be measured so that a ring selection technique could be applied to select sets of rings to construct uniform CSAs. Thus, a new predictive model had to be developed that would adequately account for the modal coupling of various modes, such as the 31- and 33-modes and that could be used to determine all three parameters, d_{33}, C_T, and C_c' for ceramic rings. Such a model and corresponding technique was developed. The technique that uses the model is called the Modal Decoupling Resonance Method (MDRM) for ceramic ring parameter determination [1,2].

Modal Decoupling Resonance Method (MDRM)

The main steps in developing the MDRM for piezoelectric ceramic ring parameter determination are:

1. Use finite-element theory to produce a predictive model that includes all important coupled modes of vibration for the subject ceramic rings.

2. Apply the MDRM predictive model to determine which experimentally measurable ring performance quantities are most sensitive to changes in the parameters of interest, namely, d_{33}, ϵ_{33}^T (or equivalently C_T), and s_{33}^E (or equivalently C_c').

3. Experimentally validate the MDRM by measuring the nine chosen performance quantities using the MDRM predictive model to compute d_{33}, ϵ_{33}^T, and s_{33}^T and comparing the results to other methods of parameter estimation.

4. Apply the MDRM to determine ceramic ring parameters for the rings of interest to STRIP.

Reference 1 documents the details of the development of the MDRM. It provides details of the sensitivity study (item 2 above) that resulted in selecting the nine ring measurement quantities. These quantities are mean ring diameter, mean wall thickness, mean length, density, C_T, and the four frequencies f_{m1}, f_{n1}, f_{m2}, and f_{n2}. Multiple measurements on a given ring were found to be required to determine the indicated mean values to sufficient accuracy for subsequent satisfactory computation of the ceramic parameters, especially d_{33}.

The four frequencies discussed are:

- f_{m1} — frequency of maximum admittance for the lowest frequency mode,
- f_{n1} — frequency of maximum impedance for the lowest frequency mode (also referred to as the hoop mode),
- f_{m2} — frequency of maximum admittance for the best coupled mode, and
- f_{n2} — frequency of the maximum impedance for the best coupled mode.

Note: the best coupled mode is defined as the mode for which $(f_m^2 - f_n^2)/f_n^2$ is greatest and is also referred to as the longitudinal mode.

The predictive model for the MDRM includes a set of nonlinear equations relating the nine measurable quantities and the three ceramic ring parameters of interest. Given values for the nine measurable quantities and initial estimates (i.e., baseline values) for the three ceramic ring parameters of interest (d_{33}, ϵ_{33}^T, and s_{33}^D), the predictive model uses Newton's method to solve iteratively for the actual ceramic ring parameters.

Appendix B is a reprint of the MDRM portion of a first draft version of TR-330A ceramic ring specification. Appendix B was included to provide further insight into how the MDRM can be used in either a new application or as part of ceramic ring specification. No difficult computations are required to apply the specification of Appendix B to TR-330A ceramic rings because the sensitivity matrix has been supplied. For a new application, the complete predictive model of the MDRM would be required to generate the sensitivity matrix. In any case, the measurement requirements are greater than for previous ceramic ring specifications.

Ratio Method for Ceramic Ring Parameters

Something equivalent to the development and application of the MDRM just described was necessary to decide whether d_{33} for rings could be determined with sufficient accuracy to make it possible to develop a DAS-7-type 33-mode ceramic ring specification. Once this problem was solved, however, a further objection was that the measurements involved in the MDRM were thought to be too expensive for production application of the FSP, especially for application to every ring, as required by the DAS-7-type ring selection procedure. Of the nine measurement quantities required (mean diameter, mean wall thickness, mean length, density, C_T, f_{m1}, f_{n1}, f_{m2}, f_{n2}) for each ring, the most expensive measurements were the multiple measurements needed to establish the mean diameter, mean wall thickness, and mean length.

Thus, for the purposes of the FSP a less expensive simplified ring parameter determination method was developed and verified. This simplified method is called the Ratio Method (RM). The RM is based on the assumption that even though the classical one-dimensional (long thin rod) model [8] is not adequate to use in a resonance method to compute absolute values for ring parameters, it will be adequate in some cases to approximate the ratios of parameters such as d_{33}/d_{33b}, C_c'/C_{cb}', and C_c/C_{cb}. This assumption was first tested by using the MDRM predictive equations. This indicated that the assumption should be very applicable to the ceramic rings in the TR 317R and TR-330A transducers. As shown later, this assumption was experimentally shown to be very adequate for rings with the dimensions used in both the TR-317 and the TR-330A transducers. For use with different relative dimensions, the assumption should be checked on a case-by-case basis.

In the RM (as in the MDRM) the low-frequency capacitance C_T is a measured quantity. Appendix C shows that starting with the usual long thin rod (one-dimensional) resonance method equations, the following equations are derived for the ratios of the other two quantities of interest in DAS-7, that is, d_{33} and C_c':

$$\frac{C_c'}{C_{cb}'} = \left[\frac{f_{n2b}^2}{f_{n2}^2}\,\frac{m_b}{m}\right], \tag{28}$$

and

$$\frac{d_{33}}{d_{33b}} = \left[\frac{C_T}{C_{Tb}}\right]^{1/2} \left[\frac{C_c'}{C_{cb}}\right]^{1/2} \left[\left(\frac{K_{33}^2}{K_{33b}^2}\right)\left(\frac{1-K_{33b}^2}{1-K_{33}^2}\right)\right]^{1/2}, \tag{29}$$

where

$$K_{33}^2 = \frac{\pi}{2}\left[\frac{f_{m2}}{f_{n2}}\right] \tan\left[\frac{\pi}{2}\left(\frac{f_{n2}-f_{m2}}{f_{n2}}\right)\right] \tag{30}$$

In Eqs. (28) and (29) all quantities with a subscript b refer to baseline quantities. In a ceramic ring specification, all such baseline quantities would be supplied as part of the specification. For example, f_{n2b}, f_{m2b}, m_b, and C_{Tb} could be measured for a given baseline ring and supplied as part of the specification. C_{cb}' and d_{33b} would also be supplied as part of the specification and would have been computed by the originator of the specification using the MDRM.

To apply the RM to new rings, f_{m2}, f_{n2}, m, and C_T must be measured for each ring. These measurements are not expensive, and thus the new DAS-7-type ceramic ring specification, including the ring selection procedure, is as economical to apply as the old 31-mode ring specifications.

Initial Application of the Ratio Method

Examples of the initial comparison of the RM with the MDRM are presented to show the excellent agreement between the two methods. To make this comparison, the output of a Ring Summary Computer Program is explained and used. Table 1 is the product of the Ring Summary Program for four different rings.

For each ring, the first portion of Table 1 is labeled Baseline File. This portion lists the input and output quantities (the baseline output is computed by using MDRM only) for the baseline rings that are to be duplicated. Most of the designators for these quantities are self-explanatory. Three designators that may not be clear are: DAP, days after poling; TEMP, the ring temperature when the data were measured; CAP, low-frequency capacitance (which elsewhere in this report is given the symbol C_T); and G, which is given by

$$G = \frac{g_{33}\,\ell}{A} = \frac{d_{33}}{C_T}. \tag{31}$$

The significance of G is that when DAS-7 is applied (as was the case for the data of Table 1), then G (after aging) should automatically be equal to the baseline value.

The next portion of the Ring Summary Program output starts by printing the Ring Serial Number and the input parameters for that ring. If (as in the case of rings H-3-223 and H-3-224) there are data for various values of DAP, then there is a print-out of the corresponding input data for each DAP entry.

Table 1 — Ring Summary Program for Four Different Ceramic Rings

BASELINE FILE 330BSE1KHZ

Mean Diameter = 1.747 in. = 4.437 cm
Wall Thickness = .2508 in. = .6371 cm
Length = .4311 in. = 1.095 cm | Area = 8.8807 cm^2
Mass = 72.97 gm | Density = 7504 kg/m^3

d_{33} (m/V)	C_c' (m/N)	C_c (m/N)	G(V/N)
291.1E^{-12}	101.3E^{-12}	193.5E^{-12}	.317

No.	DAP	TEMP (C)	f_{m1} (Hz)	f_{n1} (Hz)	f_{m2} (Hz)	f_{n2} (Hz)	CAP (pF)	d_{33} (m)
	250	23.0	23596.6	25226.8	143834	182496	918.8	334

RING SERIAL H-3-203

Mean Diameter = 1.75 in. = 4.445 cm
Wall Thickness = .2505 in. = .6363 cm
Length = .4319 in. = 1.097 cm | Area = 8.8851 cm^2
Mass = 73.51 gm | Density = 7510 kg/m^3

No.	DAP	TEMP (C)	f_{m1} (Hz)	f_{n1} (Hz)	f_{m2} (Hz)	f_{n2} (Hz)	CAP (pF)	d_{33} (m)
1	400	23.0	23494.1	25014.9	144693	182534	923.0	320

DAS-7 Parameter Ratios

No.	C_T/C_{Tb}	d_{33}/d_{33b}		C_c'/C_{cb}'		C_c/C_{cb}		G/G_b	
	Meas.	Modal	Ratio	Modal	Ratio	Modal	Ratio	Modal	Ratio
1	1.005	0.981	0.983	0.996	0.992	0.978	0.979	0.977	0.979

INTERMEDIATE CALCULATIONS FOR RATIO METHOD (SN-H-3-203)
Ratios Relative to Baseline

No.	C_T	M	f_{n2}	f_{m2}	k_{33}^2	$1-k_{33}^2$
1	1.00456	1.00740	1.00021	1.00597	0.99125	1.01303

Factors Relative to Baseline

No.	$C_c' = f_{n2}^{-2} * \mathrm{m}^{-1}$			$d_{33} = C_T^{1/2} * C_c'^{1/2} *$ KTERM			
1	0.9922	0.9996	0.9927	0.9833	1.0023	0.9961	0.9849

Table 1 (continued) — Ring Summary Program for Four Different Ceramic Rings

RING SERIAL H-3-204

Mean Diameter = 1.75 in. = 4.444 cm
Wall Thickness = .2495 in. = .6337 cm
Length = .4315 in. = 1.096 cm — Area = 8.8472 cm^2
Mass = 72.45 gm — Density = 7480 kg/m^3

No.	DAP	TEMP (C)	f_{m1} (Hz)	f_{n1} (Hz)	f_{m2} (Hz)	f_{n2} (Hz)	CAP (pF)	d_{33} (m)
1	400	23.0	23525.7	25080.5	144763	183153	920.0	321

DAS-7 Parameter Ratios

No.	C_T/C_{Tb}	d_{33}/d_{33b}		C_c'/C_{cb}'		C_c/C_{cb}		G/G_b	
	Meas.	Modal	Ratio	Modal	Ratio	Modal	Ratio	Modal	Ratio
1	1.001	0.990	0.993	0.999	1.000	0.989	0.994	0.989	0.992

INTERMEDIATE CALCULATIONS FOR RATIO METHOD (SN-H-3-204)
Ratios Relative to Baseline

No.	C_T	M	f_{n2}	f_{m2}	k_{33}	$1-k_{33}^2$
1	1.00129	0.99287	1.00360	1.00646	0.99570	1.00643

Factors Relative to Baseline

No.	$C_c' = f_{n2}^{-2} * m^{-1}$			$d_{33} = C_T^{1/2} * C_c'^{1/2} *$ KTERM			
1	1.0000	0.9928	1.0072	0.9931	1.0006	1.0000	0.9925

Table 1 (continued) — Ring Sumary Program for Four Different Ceramic Rings

RING SERIAL H-3-223

Mean Diameter = 1.75 in. = 4.445 cm
Wall Thickness = .25 in. = .635 cm
Length = .4315 in. = 1.096 cm — Area = 8.8674 cm^2
Mass = 72.75 gm — Density = 7486 kg/m^3

No.	DAP	TEMP (C)	f_{m1} (Hz)	f_{n1} (Hz)	f_{m2} (Hz)	f_{n2} (Hz)	CAP (pF)	d_{33} (m)
1	14	23.0	23219.7	24833.3	142758	182879	977.0	345
2	31	23.0	23285.5	24894.5	143183	183123	964.0	340
3	60	23.0	23339.3	24935.5	143515	183199	961.1	336
4	101	23.0	23380.4	24965.9	143733	183148	944.2	334

DAS-7 Parameter Ratios

No.	C_T/C_{Tb}	d_{33}/d_{33b}		C_c'/C_{cb}'		C_c/C_{cb}		G/G_b	
	Meas.	Modal	Ratio	Modal	Ratio	Modal	Ratio	Modal	Ratio
1	1.063	1.055	1.057	0.997	0.999	1.021	1.021	0.992	0.994
2	1.049	1.042	1.044	0.994	0.996	1.014	1.014	0.994	0.995
3	1.046	1.035	1.037	0.994	0.995	1.008	1.009	0.989	0.991
4	1.028	1.021	1.023	0.995	0.996	1.004	1.006	0.994	0.995

INTERMEDIATE CALCULATIONS FOR RATIO METHOD (S/N H-3-223)
Ratios Relative to Baseline

No.	C_T	M	f_{n2}	f_{m2}	k_{33}	$1-k_{33}^2$
1	1.06333	0.99699	1.00210	0.99252	1.01418	0.97864
2	1.04918	0.99699	1.00343	0.99547	1.01180	0.98224
3	1.04603	0.99699	1.00385	0.99778	1.00902	0.98645
4	1.02763	0.99699	1.00357	0.99929	1.00637	0.99044

Factors Relative to Baseline

No.	$C_c' = f_{n2} * m^{-1}$			$d_{33} = C_T^{1/2} * C_c'^{1/2} *$ KTERM			
1	0.9988	0.9958	1.0030	1.0565	1.0312	0.9994	1.0252
2	0.9962	0.9932	1.0030	1.0437	1.0243	0.9981	1.0209
3	0.9953	0.9923	1.0030	1.0366	1.0228	0.9977	1.0159
4	0.9959	0.9929	1.0030	1.0230	1.0137	0.9979	1.0112

Table 1 (continued) — Ring Summary Program for Four Different Ceramic Rings

RING SERIAL H-3-224

Mean Diameter = 1.753 in. = 4.451 cm

Wall Thickness = .2505 in. = .6363 cm

Length = .4315 in. = 1.096 cm Area = 8.8978 cm^2

Mass = 73.15 gm Density = 7501 kg/m^3

No.	DAP	TEMP (C)	f_{m1} (Hz)	f_{n1} (Hz)	f_{m2} (Hz)	f_{n2} (Hz)	CAP (pF)	d_{33} (m)
1	14	23.0	23161.4	24771.4	142754	182669	994.5	351
2	31	23.0	23238.7	24837.2	142993	182841	981.2	340
3	60	23.0	233284.8	24880.4	143340	183125	976.0	338
4	101	23.0	23322.9	24902.4	143553	182943	962.1	336

DAS-7 Parameter Ratios

	C_T/C_{Tb}	d_{33}/d_{33b}		C_c'/C_{cb}		C_c/C_{cb}		G/G_b	
No.	Meas.	Modal	Ratio	Modal	Ratio	Modal	Ratio	Modal	Ratio
1	1.082	1.059	1.061	0.994	0.996	1.013	1.015	0.978	0.980
2	1.068	1.049	1.051	0.992	0.994	1.010	1.011	0.982	0.984
3	1.062	1.042	1.044	0.989	0.991	1.005	1.006	0.981	0.983
4	1.047	1.029	1.031	0.991	0.993	1.000	1.003	0.982	0.985

INTERMEDIATE CALCULATIONS FOR RATIO METHOD (S/N H-3-224)

Ratios Relative to Baseline

No.	C_T	M	f_{n2}	f_{m2}	k_{33}	$1-k_{33}^2$
1	1.08238	1.00247	1.00095	0.99249	1.01255	0.98110
2	1.06790	1.00247	1.00189	0.99415	1.01149	0.98272
3	1.06224	1.00247	1.00344	0.99656	1.01021	0.98464
4	1.04711	1.00247	1.00245	0.99804	1.00657	0.99014

Factors Relative to Baseline

No.	$C_c' = f_{n2}^{-2} * m^{-1}$			$d_{33} = C_T^{1/2} * C_c'^{1/2} *$ KTERM			
1	0.9957	0.9981	0.9975	1.0612	1.0404	0.9978	1.0223
2	0.9938	0.9962	0.9975	1.0511	1.0334	0.9969	1.0203
3	0.9907	0.9931	0.9975	1.0444	1.0307	0.9953	1.0181
4	0.9927	0.9951	0.9975	1.0313	1.0233	0.9963	1.0116

DAS-7 Parameter Ratios is the next portion of the Ring Summary Computer Program output. The ratio of the given quantity to the baseline value (the subscript b stands for baseline value) is listed. For C_T the ratio C_T/C_b is a measured quantity, that is, neither the MDRM nor the RM is used. For the other quantities, both the MDRM- and RM-derived ratios are displayed.

Intermediate Calculations for the Ratio Method is the next portion of the Ring Summary computer output. This is used to gain insight into which factors, according to the RM, are significantly contributing to the aging rates, and it is subdivided into two subparts. The first subpart is Ratios Relative to Baseline. Under the heading C, values (for the Ratio Method) are found for C_T/C_{Tb} (a repeat from the DAS-7 Parameter Ratio Part), under M are found values of M/M_b, under f_{ms} is listed f_{m2}/f_{m2b}, under f_{n2} is f_{n2}/f_{n2b}, under k_{33} is k_{33}/k_{33b}, and under the heading 1-k_{33} sq. are found $(1\text{-}k_{33}^2/1\text{-}k_{33b}^2)$.

The second subpart, Factors Relative to Baseline, lists the factors as they appear in the equations of the ratio method as follows:

The heading $C_c' = f_{n2} -2* \ M$-1 stands for Eq. (28);
$d_{33} = C_T 1/2 \ * C'1/2$ * KTERM stands for Eq. (29).

Table 1 shows data for four different ceramic rings (four preliminary rings associated with the Honeywell third-iteration rings discussed in Evaluation of Third-iteration Honeywell TR-330A Rings. Two of the rings were well aged (S/Ns H-3-203 and H-3-204); when first measured, the other two rings (S/Ns H-3-223 and H-3-224) were unaged (14 days after poling) when received.

Table 1 includes a Ring Summary computer program output of both the old and new data for rings H-3-223 and H-3-224 (four different DAP entries for each ring). Also included for easy comparison are the two DAP entries for each of the aged rings, H-3-203 and H-3-204. Table 1 data suggest at least four conclusions:

1. As claimed by Honeywell, the parameter values for the two unaged rings are indeed converging with time to those of the two aged rings.

2. The RM gives almost the same answers as the more expensive MDRM. Thus, the RM can be used with confidence in the DAS-7-type ceramic ring specifications for at least the TR-330A-type ceramic rings. However, the RM requires an initial application of the MDRM by the developer of the specification to establish the baseline values for the parameters.

3. The factor $G = g_{33}\ell/A$ has essentially finished aging in the first 30 days or less [At the time, no data were available for less than 30 days. Subsequent data indicate the time may be considerably less than 30 days after poling (see Appendix E)]. Therefore after 30 days and since $d_{33} = C_T G$, the after-30-days or less d_{33} should age at about the same rate as C_T. This was important because there was a vast amount of aging data for C_T but very little data for the important DAS-7 parameter d_{33}.

4. The frequency f_{n2} and thus the open-circuit compliance C_c' have essentially finished aging in the first 30 days or less [At the time no data were available for less than 30 days. Subsequent data indicate that the time may be considerably less than 30 days after poling (see Appendix E)]. A similar statement is not true for f_{m2} or the short-circuit compliance C_c.

Accuracy of the Ratio Method

Experimental data for six Honeywell third-iteration TR-330A rings were analyzed by both the MDRM and the RM. In the initial applications the agreement between these two techniques had been spectacular, usually much better than 1%. Several of the Honeywell rings, however, showed differences approaching 2%. Although this was still good agreement, it was so much worse than had been obtained previously that it motivated an investigation of the source of the disagreement [9].

The experimentalists remeasured the dimensions of the rings at a number of positions around the circumference and found that the length and outside diameter did not vary significantly with position, but that the wall thickness τ had considerable variation. Based on these measurements, the analysts developed the following technique to determine an effective τ for use in the MDRM (assuming that the RM results were correct).

It was assumed that the density ρ, the mass m, the length ℓ, and the o.d. could be measured accurately. The cross-sectional area A should then be given approximately by

$$A = \frac{m}{\rho \ell} . \tag{32}$$

For a ring of constant wall thickness τ, the area is also given by

$$A = \pi\tau\,(OD - \tau) . \tag{33}$$

Equating these two expressions for A gives the quadratic equation for τ:

$$\tau^2 - \tau\,(OD) + \frac{m}{\pi\rho\ell} = 0 . \tag{34}$$

The only admissible solution to this equation is

$$\tau = \frac{OD - [(OD) - (4m/\pi\rho\ell)]^{1/2}}{2} . \tag{35}$$

By using this expression to calculate an effective τ for use in the MDRM, the agreement between the MDRM and the RM was again spectacular. For example, the ratio of d_{33} to the baseline value d_{33b} for ring H-3-239 was originally computed to be

$$\frac{d_{33}}{d_{33b}} = 1.040 \text{ by using the Modal Method, and } 1.053 \text{ by using the Ratio Method.}$$

With the effective τ computed as shown above, *both methods* gave 1.053.

As a further check of these results, the wall thickness was measured at many more locations around the ring. These values were used to compute a new mean value for the wall thickness that turned out to be very close to the effective wall thickness estimated as above. Thus, the RM gave a more accurate answer than did the MDRM until greater care was exercised in measuring the effective wall thickness as an input to the MDRM. *However, remember that a one-time highly accurate application of the Modal Decoupling Resonance Method is required before applying the Ratio Method to obtain absolute values for ring parameters.*

Robustness of the Ratio Method

This subsection describes an application of the RM that at first appeared to cast some doubt on the RM but ultimately demonstrated that it was even more robust and useful than initially expected. This application occurred as part of the STRIP CSA Sample Buys mentioned briefly in the section TR-317R CSAs Using Almax Rings from CSA Sample Buys and described in some detail in Appendix E.

The ceramic ring specification for the TR-317R, NAVSEA Dwg. No. 53711-5516940, calls for a CSA d_{33} (i.e., d_{33bs}) of 243.6 $\times$ 10^{-12} m/V $\pm 2\%$. As a result of data from the CSA sample buys, questions were raised concerning the accuracy of the specified RM in determining the d_{33} of ceramic rings. The sample buy data indicated an error in d_{33} of $\sim 1.5\%$.

The apparent error in d_{33} became evident when one of the sample buy ceramic suppliers (Almax) increased the ceramic ring area by $\sim 3\%$ to obtain the specified free capacitance and d_{33}. However, the dimensions of the rings were within the dimensional tolerances for the ceramic ring as given in NAVSEA Dwg. No. 53711-5516940, Fig. 1. (In this report Fig. 1 of the drawing is shown as Fig. 7; all references to Fig. 7 are for Fig. 1 of NAVSEA Dwg. No. 53711-5516940.) When the d_{33} values for the rings were determined by using the government-supplied baseline area data and the baseline area +3% data (at that time the ceramic specification contained a government-supplied data set for ceramic areas of baseline -6%, baseline -3%, baseline, baseline +3%, and baseline +6%), the error was noted; the latter provided a higher value of d_{33}. Since the Contractor's rings were within the dimensional tolerances of Fig. 7, there should have been very close agreement in the computed values of d_{33} regardless of which data set was used for the computation.

It was at first feared that the RM for ceramic ring parameter determination might be sensitive to small dimensional variations. That is, in addition to the baseline data, the government might be required to supply data for areas of, say 1%, 1.5%, 2%, 2.5%, etc. This led to the question: how does one determine if the RM is sensitive to small dimensional variations? The answer, of course, was to conduct a worst-case dimensional/parameter analysis on the TR-317R ceramic ring specification, including situations where the worst-case capacitance occurs, to determine the effects on d_{33}.

The worst cases are allowed by the tolerances on the dimensions as shown in Fig. 7 and by the specification (Dwg. 53711-5516940) for ring free capacitance; C_T = 1564 pF $\pm 10\%$. Note in each worst-case that is identified, if there is an MA (maximum area) in the designator, the ring has an area 3.4% greater than a baseline ring with basic value dimensions, and, if there is an MI (minimum area) in the designator, the ring has an area 3.32% less than a baseline ring with basic value dimensions. These areas are allowed by the tolerances on the basic value dimensions in Fig. 7, without evoking the one-time area adjustment allowed by the specification. Therefore, if there is a population of rings with dimensions tending to either the high side or the low side of the tolerance band, it is reasonable, in terms of the accuracy of the computed quantities, to interchangeably use the +3% or -3% government-supplied data to compute d_{33}.

NOTES:

1. ELECTRODES SHALL BE FIRED SILVER 0.0005/0.0015 THICK.
2. ELECTRODES SHALL COVER THE LATERAL END SURFACES OF THE RING.
3. 0.020 MAXIMUM CHAMFER ON CORNERS.
4. INSIDE AND OUTSIDE SURFACES SHALL BE GLAZED "AS-FIRED" SURFACE, EXCEPT AS SPECIFIED IN 3.1.8.1.1.
5. BASELINE WALL THICKNESS IS 0.370 INCHES BUT MAY BE ADJUSTED AS SPECIFIED IN PARAGRAPH 3.2.1.2, ITEM A.

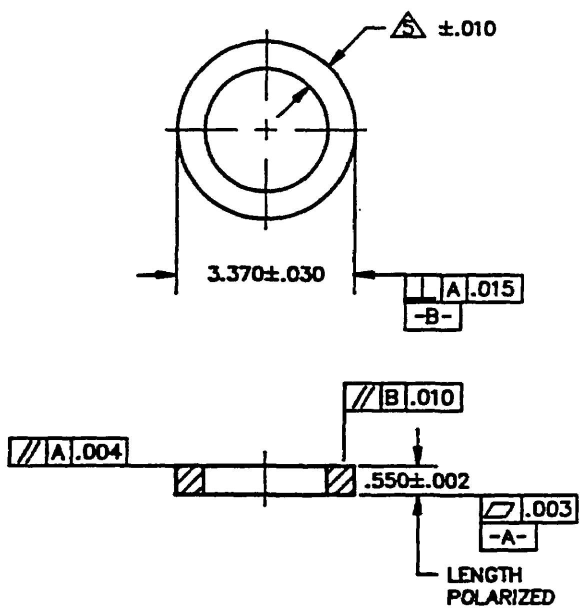

Fig. 7 — TR-317( ) ceramic ring drawing from NAVSEA Dwg. 53711-5526940

The following is the designation and description of the ideal situation (1BL) and eight possible worst-case situations that will be used for the analysis (all dimensions and tolerances are given in Fig. 7):

1BL — Baseline ceramic ring with basic value dimensions; the benchmark, ideal ring.

2MAT — Ring with the maximum area and the minimum length allowed, with a baseline dielectric constant, a ring with maximum capacitance; C_T = 1624 pF.

3MAL — Ring with the maximum area and the maximum length allowed; with a baseline dielectric constant, the capacitance of this ring is slightly less than maximum; C_T = 16112 pF.

4MATC — Ring with maximum area and the minimum length allowed; the dielectric constant is adjusted to give a ring with the maximum capacitance allowed by the ceramic ring specification; C_T = 1564 pF + 10% or 1720 pF.

5MALC — Ring with the maximum area and the maximum length allowed; adjusting the dielectric constant to the same value as in 4MATC gives a ring with a capacitance slightly less than the maximum allowable capacitance; C_T = 1707.5 pF.

6MIT — Ring with the minimum area and the maximum length allowed (just the opposite of 2MAT); a baseline dielectric constant gives a ring with minimum capacitance; C_T = 1507 pF.

7MIL — Ring with the minimum area and the minimum length allowed; with a baseline dielectric constant, a ring with a capacitance slightly more than minimum, C_T = 1518 pF.

8MITC — Ring with the minimum area and the maximum length allowed; the dielectric constant is adjusted to give the minimum capacitance allowed by the specification; C_T = 1564 pF −10% or 1408 pF.

9MILC — Ring with the minimum area and the minimum length allowed; with the dielectric constant adjusted to the same value as in 8MITC, this gives a ring with a capacitance slightly more than the minimum allowable capacitance; C_T = 1418 pF.

After the worst-case rings were identified, the MDRM RINGFREQ program [2] was used to generate, from a best estimate of the ceramic piezoelectric parameters, the frequencies (longitudinal and hoop mode resonance and antiresonance) for the nonexisting rings. They were nonexisting in that, except for 1BL, the rings exist only in theory. The frequencies determined by RINGFREQ were entered into the RINGPARAM program [2] to find the piezoelectric parameters for each worst-case ring. The process was iterated until the parameters and frequencies from both programs converged; the d_{33} thus found is considered to be "truth"—the best and most accurate value of d_{33} for each worst-case ring.

After the parameters and frequency data were obtained for the worst-case rings, the data were used to systematically compute, by the MDRM and by the RM, using the government-supplied data sets in the ceramic ring specification, the d_{33} of each ring to determine the error in the computation. Table 2 is a summary of the computed d_{33} data.

The second column in Table 2 (Modal Method—Exact Area) shows the d_{33} computed by the MDRM for the baseline and the worst-case rings. This column contains the truth or benchmark value of d_{33} for each ring. The third column in Table 2 (Modal Method—Baseline Area) shows the d_{33} computed by the MDRM for the baseline and the worst-case rings. However in this case the d_{33} was computed by using baseline-area parameters and dimensions instead of the exact-area parameters and dimensions. In every case the difference between the column 2 and column 3 data is <0.1% except for the 8MITC case where the difference is 0.14%.This shows that the MDRM is not sensitive to small dimensional variations; it can handle area variations about the baseline from −3.32 to 3.4% (area difference between the worst-case minimum and maximum area rings) with no significant error. However, the robustness and accuracy of the MDRM has been previously proven and reported; here it serves as a benchmark. But, remember that the MDRM was originally in the ceramic ring specification (FSP) and was replaced by the RM because the former required too many measurements to be practical and would be expensive when used in large-scale production.

Table 2 — Summary of d_{33} Data (All Values are 10^{-12} m/V) for Worst-Case Physical Dimensions Compared to Ideal Case (1BL)

Modal Method			Ratio Method			
Ring No.	Exact Area	Baseline Area	Baseline Area	+3% New (Old)	−3% New (Old)	+6% New (Old)
1BL	243.63	243.63	243.69			
2MAT	243.63	243.59	243.56	243.78	245.06 (247.33)	243.99
3MAL	243.63	243.59	243.41	243.64	244.91 (247.18)	243.84
4MATC	250.43	250.62	250.68	250.91	252.22 (254.56)	251.12
5MALC	250.43	250.57	250.53	250.76	252.07 (254.40)	250.97
6MIT	243.63	243.60	242.30	242.53	243.8	242.78 (240.01)
7MIL	243.63	243.59	242.51	242.73	244.0	242.93 (240.2)
8MITC	235.11	235.43	234.23	234.44	235.67	236.64 (232.01)
9MILC	235.12	235.34	234.42	234.64	235.87	234.83 (232.20)

Table 2, column 4 (Ratio Method—Baseline Area) shows the d_{33} for the baseline and the worst-case rings computed by the RM. The baseline values used in the computations are for a baseline ring with an area that corresponds to the basic value dimensions in Fig. 7 (baseline area quantities in ceramic ring specification). A small but still insignificant error is noted between the data in column 2 and the data in column 4 (<0.6% in all cases and typically <0.3%). This shows that the RM using baseline area data is robust enough to handle the area differences of the worst-case rings (rings within the dimensional tolerances of Fig. 7) and predict the d_{33} with a small but still insignificant error.

The numbers in parenthesis in columns 5 and 6 are the d_{33} computed by using the data in the then-existing ceramic ring specification (baseline area +3% and −3%) that most closely correspond to the actual area of the worst-case rings. In every case the computed d_{33} should be very close to the appropriate exact area benchmark value in column 2, but a significant error is noted. For the +3% data the error is from 1.5 to 1.7% and for the −3% data the error is from 1.2 to 1.5%. *From this data it was evident that the government-supplied, area-adjusted data in the ceramic ring specification must be wrong.*

All the information that went into the government-supplied data was reviewed, and the reason for the indicated discrepancy was found. When the data for the −3%, +3%, and +6% area rings were initially evaluated, the requirements of DAS-7 were not properly observed. Recall that DAS-7 requires a d_{33} and a free capacitance match to duplicate the ceramic. If both cannot be matched, the d_{33} must be matched and the ceramic ring area adjusted within prescribed limits to match the free capacitance. In terms of the interdependency of the piezoelectric constants, when the ϵ_{33}^{T} goes up, the area must go down; when the ϵ_{33}^{T} goes down, the area must go up. Thus, a change occurs in g_{33} inverse to that of the dielectric constant that keeps d_{33} constant. When the original area-adjusted data were computed (that presently in the specification) the dielectric constant was not changed. The frequencies in the data sets correspond to rings that have a free capacitance greater than the baseline in the increased area cases and to a free capacitance less than baseline for decreased area cases. This is contrary to the requirements of DAS-7. It was also found that the same thing had occurred in the TR-330A ceramic ring specification. In both specifications, only the baseline area data set was correct.

As a result of the these findings, the area-adjusted data for both the TR-317R and the TR-330A was recalculated by using the MDRM and rigorously following the requirements of DAS-7. Columns 4, 5, and 6 of Table 2 show the new value of d_{33} calculated by using the new area-adjusted data for each TR-317R worst-case ring. Now there is no significant error (typically $<0.2\%$) in the cases where the selected data set most closely corresponds to the exact area of the ring. The largest error occurs when the −3% data is used for the maximum area rings—from ~0.5 to 0.7%.

The results from the new data in Table 2 strongly suggest that by accepting a small, almost insignificant error in d_{33} the ceramic specification *can be changed to have only one set of government-supplied data.* Subsequently, the decision was made to further test the robustness of the RM by using the TR-317R baseline-area data to compute the d_{33} of the area-adjusted rings. In other words, the baseline area −3%, baseline area +3%, and baseline area +6% data are representative of rings that have each of the respective areas; therefore, the area-adjusted ring data can be used to simulate an existing ring in the same manner as were the worst-case rings.

Table 3 shows the TR-317 baseline area data and the new area-adjusted data. Column 5 also shows the d_{33} computed for the area-adjusted rings by using the TR-317 baseline area data as the baseline quantities in the ratio equation. The difference, shown in column 6, is 0.33% in the worst-case situation.

Based on the indicated excellent robustness of the RM, an extreme test of the RM was conducted that was well beyond any actual planned application of the RM in a ceramic ring specification (FSP). Specifically, the baseline data for the TR-317R rings were used as "the government-furnished data" to calculate the parameters of a totally different ring—a TR-330A ceramic ring.

The TR-330A ceramic ring specification data was used as if it were the experimentally measured data for the test. In this case the new TR-330A baseline-area data and the new area-adjusted data (baseline area +3% and baseline area +6%) were used to represent rings with a supposedly unknown d_{33}. Table 3 shows the results of the test. Note the differences between the TR-317R ceramic ring and the TR-330A ceramic ring, respectively: o.d., 3.370 vs 2.0 in.; wall .370 vs 0.250 in.; length, 0.550 vs 0.430 in.; free capacitance, 1564 vs 966 pF; mass, 0.2386 vs 0.07328 kg; and d_{33}, 243.6×10^{-12} vs 302.2×10^{-12} m/V.

Table 3 — Summary of the d_{33} Data Calculated by the RM Using the TR-317R Baseline Area Data as the Baseline in Every Case

	f_m (kHz)	f_n (kHz)	C_T (10^{-12} pF)	m (kg)	d_{33} (10^{-12} m/V)	Δd_{33} %
TR-317 Baseline Area	117.0083	143.3899	1564	.2386	243.6*	0
Baseline Area +3%	115.7428	142.1149	1564	.2457	244.1	0.21
Baseline Area −3%	118.4905	144.6341	1564	.2314	242.8	−0.33
Baseline Area +6%	114.4553	140.7088	1564	.2529	243.9	0.12
TR-330A Baseline Area	142.9547	182.3653	966	.07328	304.2 302.2*	24.9 0.66
Baseline Area +3%	141.4966	181.6988	966	.07548	304.9	25.2 0.89
Baseline Area +6%	140.4421	180.9315	966	.07768	305.4	25.4 1.06

*TR-317 and TR-330A baseline value of d_{33}, respectively.

Table 3, rows 5, 6, and 7 show the new TR-330A baseline-area data, the new baseline-area +3% data, and the new baseline-area +6% data, respectively. Column 6 shows the d_{33} for the TR-330A rings calculated by the RM method using the TR-317R baseline-area data as the baseline data. The computed d_{33} for the TR-330A baseline-area ring (row 5) is 304.2×10^{-12}, which is 24.9% greater than the TR-317R baseline, as shown in column 7. But, the baseline value of d_{33} for the TR-330A is 302.2×10^{-12} (indicated in row 5, column 6 by an asterisk), and the difference between the TR-330A baseline d_{33} and that computed using the TR-317R data is only 0.66% (shown by an asterick in row 5, column 7). Table 3 also shows the difference between the TR-317R baseline d_{33} and the TR 330A baseline d_{33} for the other ring areas.

The results of the last test indicated that the RM was indeed very robust. The maximum error in the true value of d_{33} was <1.1% in all cases when the d_{33} for the TR-330A rings was found by using the TR-317R baseline ceramic ring data. As a final test, the TR-330A baseline-area data were used to compute the d_{33} for the TR-330A baseline area +3% and baseline area +6% rings. The results (not shown in a table) indicated an error of 0.2 and 0.36%, respectively.

In summary, this series of tests confirmed that a given ceramic ring specification need contain only one well-defined government-furnished baseline data set for use with the RM to compute the d_{33}. Tables 4 and 5 show the new baseline government-supplied data sets for the TR-317R and the TR-330A. The old data are also shown in the tables for comparison. NAVSEA Dwg. Nos. 53711-5516940 and 53711-5517076 were revised to reflect the new data. However, each revised drawing contains only one data set, i.e., the baseline-area data set. This simplified the drawings and made them more easily understood.

Table 4 — Comparison of Old and New TR-317R Government-Supplied Baseline Data Sets

	d_{33} (10^{-12} m/V)	C_T (pF)	C_c' (10^{-12} m/N)	F_m (kHz)	F_n (kHz)	m (kg)
			Baseline			
Old	243.6	1564	47.295	117.0830	143.3899	.23722
New	243.6	1564	47.295	117.0083	143.3899	.2386
			+3% Area			
Old	243.6	1564	45.918	116.2951	142.1032	.2457
New	243.6	1564	45.917	115.7428	142.1149	.2457
			−3%			
Old	243.6	1564	48.758	117.8293	144.5579	.2314
New	243.6	1564	48.692	118.4905	144.6341	.2314
			+6% Area			
Old	243.6	1564	44.618	115.4649	140.6868	.2529
New	243.6	1564	44.616	114.4553	140.7088	.2529

Table 5 — Comparison of Old and New TR-330A Government-Supplied Baseline Data Sets

	d_{33} (10^{-12} m/V)	C_T (pF)	C_c' (10^{-12} m/N)	F_m (kHz)	F_n (kHz)	m (kg)
			Baseline			
Old	302.6	966	10.1	143.043	182.3669	.07328
New	302.2	966	10.11	142.9547	182.3653	.07328
			+3% Area			
Old	302.2	995	9.806	142.4948	181.6823	.07548
New	302.2	966	9.811	141.696	181.6988	.07548
			+6%			
Old	302.2	1024	9.528	141.9114	180.9122	.07768
New	302.2	966	9.533	140.4421	180.0315	.07768

33-MODE CERAMIC RING SPECIFICATION

STRIP developed a new 33-mode-type ceramic ring specification by using the above-described DAS-7 concepts and CSA and ceramic ring parameter measuring techniques. Appendix D contains a complete example of the resulting specification for the TR-330A transducer. The best way to understand this new 33-mode ceramic ring specification is to read Appendix D and relate it to the other material in this report.

The reader should be aware of the following points in Appendix D:

1. Although the specification makes provisions for iteration on the Piezoelectric Ceramic Material Qualification Procedure (Section 3.2), it has never been found necessary to iterate on rings that met the baseline requirements of Section 3.1.10.

2. Although a ceramic ring area adjustment is allowed to make $C_T = C_{Tb}$, in all trial attempts thus far the ring supplier has found it possible to make $C_T = C_{Tb}$ (and at the same time $d_{33} = d_{33b}$) without evoking the area adjustment. However, although not yet found necessary, such an allowable area adjustment could have been useful.

3. The Approved Ring Production Set concept of the specification (Section 3.3) allows contractors to apply their best technique (proprietary or otherwise) to produce a good yield on rings, but at the same time in conjunction with the ingredients lot qualification procedure, provides timely confidence to the customer that a satisfactory set of ceramic rings is being produced.

4. In conjunction with the Ratio Method of parameter determination, the required two-parameter (see Section 3.3.b), d_{33} and C_T, ring selection procedure is no more expensive to apply than other two-parameter ring selection procedures that have been required in the past.

EXPERIMENTAL VALIDATION OF THE STRIP SOLUTION

This section describes the results of the experimental validation of the key technical features of the STRIP solution to the 33-mode piezoelectric ceramic reproducibility problem. These key features are DAS-7, the ring parameter determination procedure, and the ceramic ring-to-CSA relation. Experimental validation of DAS-7 is also considered validation of the complete Simplified Guidance Model.

As a result of this experimental validation, STRIP successfully produced and tested baseline equivalent ceramic rings and CSAs for two radically different transducer elements, the TR-317R and the TR-330A. Not only were the transducers very different from each other but each used a different ceramic type; specifically, the TR-317R uses Type III ceramic and the TR-330A uses Type I ceramic. (Note: The original baseline ceramic rings for both transducers were produced by the EDO Corporation.) For the TR-317R transducer, four suppliers were tasked to test the new ring specification. Baseline-equivalent ceramic rings and CSAs were successfully produced by all four different suppliers—GE, Honeywell Corp., Channel Industries, and Almax. For the TR-330A transducer, only Honeywell was tasked to test the new ring specification; Honeywell successfully produced TR-330A baseline-equivalent ceramic rings.

The experimental validation results using TR-317R and TR-330A components are presented in the following subsections. However, the TR-317R Sample Buy results described in Appendix E should also be considered as experimental validation of many parts of the total STRIP solution to the ceramic reproducibility problem.

TR-317R Ceramic Components

The first experimental validation involved the TR-317R transducer and was planned to be the most radical and severe test of DAS-7. It was conducted by using rings produced by the General Electric Corporation (GE), and the results are described in the next subsection.

Because of the success of the first experimental validation, the second test for the TR-317R was planned to be a straightforward (not radical) attempt to have a second supplier, Honeywell Corporation, produce baseline-equivalent rings for the TR-317R. This successful effort is described in the subsection following the GE validation. For the third experimental validation for the TR 317R, Channel Industries was chosen as the ring supplier because their standard rings differed greatly from the baseline ceramic rings.

Radical DAS-7 Experiment (Using Various GE Ceramic Formulations)

DAS-7 (and thus the SGM in general) was tested experimentally by departing deliberately and radically from the given baseline CSA piezoelectric ceramic formulation. A radical departure simply means a much greater departure from the baseline formulation than would be necessary in the usual production effort to reproduce a given CSA. Four piezoelectric ceramic formulations, each different from baseline and from each other, were used to manufacture CSAs and test DAS-7. The radical degree of departure from baseline may be inferred from the amount of ceramic ring area adjustment needed for some of the formulations to achieve step 2 of DAS-7. (Note: All rings had the baseline thickness ℓ_{cb}). Specifically, the resulting adjusted areas for step 2 were: -11.4% (this ceramic will be referred to as CR.-11), 0% (this ceramic will be referred to as CR.+0), +6% (this ceramic will be referred to as CR.+6), and +18% (this ceramic will be referred to as CR.+18).

These four radically different piezoelectric ceramic powder formulations and the ceramic rings produced from these four piezoelectric ceramic formulations were supplied by GE. The ring testing and CSA construction by using these rings were performed by the Naval Research Laboratory-Underwater Sound Reference Detachment (NRL-USRD). The remainder of the DAS-7 experimental tests described in this report were performed by the Naval Ocean Systems Center (NOSC).

Ceramic Ring Parameter Determination for the Radical DAS-7 Experiment

GE first supplied a set of rings with no area adjustment (CR.+0 rings) (also referred to as baseline-like rings). GE subsequently supplied three additional sets with the adjusted areas (CR.-11, CR.+6, and CR.+18) above. The USRD ring parameter measurement results are discussed next.

Parameters for GE Baseline-Like Rings (CR.+0)

There were 39 rings in the GE baseline-like (CR.+0) ring set. This set is referred to as the baseline-like ring set because a Type III formulation was used that resulted in a ceramic ring area the same as baseline, that is, no area adjustment was needed for the baseline-like rings. The target ceramic parameters were those corresponding to early TR-317 production and are referred to as "old baseline values." The baseline-like rings were specially prepared by GE to imitate the Gulton rings used for the early (old baseline) TR-317 production. In later production the parameters changed, and STRIP was instructed to use these new baseline values.

USRD made frequency-admittance, capacitance, dissipation, high-field, density, corona, and dimensional measurements on the rings. Table 6 shows the frequency, admittance, capacitance and dissipation mean and standard deviation data of 39 GE baseline-like rings. Table 7 shows the mean and standard deviation of the electromechanical parameters of 39 GE baseline-like TR-317R ceramic rings. Table 8 shows the mean and standard deviation of the low- and high-field capacitances, the $\Delta K_{33}^{T}\%$, and the low- and high-field loss tangent for 39 GE baseline-like TR-317R rings ~70 days after polarization.

Table 6 — Frequency, Admittance, Capacitance, and Dissipation Data, Mean and Standard Deviation of Measurements on 39 GE Baseline-like TR-317R Ceramic Rings

Frequency (kHz)	ADMITTANCE Conductance (siemens)	Susceptance (siemens)	Coupling (k)	Coupling (k_{eff})	Mode
f_r 14.4928	1.54×10^{-2}				
0.0168	2.66×10^{-3}				
			0.3054		
f_a 15.2227	1.47×10^{-6}		0.0041		
0.0227	5.06×10^{-7}				
					Hoop
f_m 14.4927	1.54×10^{-2}	5.47×10^{-4}			
0.0186	2.68×10^{-3}	4.59×10^{-4}			
				0.3060	
f_n 15.2232	1.47×10^{-5}	7.87×10^{-8}		0.0041	
0.0232	5.0×10^{-7}	8.63×10^{-8}			
f_r 119.0572	4.35×10^{-1}				
0.2721	3.57×10^{-2}				
			0.5796		
f_a 141.5177	1.54×10^{-6}		0.0042		
0.4175	7.25×10^{-8}				
					Longitudinal
f_m 119.0582	4.35×10^{-1}	4.62×10^{-2}			
0.2659	3.57×10^{-2}	1.6×10^{-2}			
				0.5800	
f_n 141.5176	1.54×10^{-6}	6.79×10^{-8}		0.0042	
0.4195	7.09×10^{-8}	6.70×10^{-8}			

Capacitance @ 1 kHz — 1598.5 pF
Standard Deviation — 20.2 pF

Dissipation — 9.8×10^{-4}
Standard Deviation — 8.7×10^{-5}

Table 7 — Mean and Standard Deviations of the Electromechanical Parameters of 39 GE Baseline-like TR-317R Ceramic Rings, 68 Days Old

	K_{33}^T	k_{33}	s_{33}^D Vm/N	s_{33}^E Vm/N	d_{33} Vm/N	g_{33} Vm/N
Mean	1125.1	0.580	8.122	12.239	202.5	20.3
Standard Deviation	13.4	0.004	0.037	0.059	2.5	0.19

Table 8 — Mean and Standard Deviation of the Low- and High-field Capacitance, the ΔK_{33}^T, and the Low- and High-field Loss Tangent for 39 GE Baseline-like TR-317R Ceramic Rings (60 Hz data)

C (100 V rms) (pF)	C (5.6 kV rms) (pF)	ΔK_{33}^T	tan δ (100 V)	tan δ (5.6 kV)
$\bar{x}$ 1618	1679	4.89	0.0021	0.0082
s 21	22	0.15	0.00016	0.00036

Density measurements by the Archimedes method gave a mean density of 7.787×10^3 kg/m^3 with a standard deviation of 0.0374. The results of the above measurements were compared with measurements by GE on the rings, and there was excellent agreement between the data. More recent measurements on 300 old baseline rings, ~450 days old, showed the following characteristics: $K_{33}^T = 1077$; $k_{33} = 0.551$; $s_{33}^D = 8.666 \times 10^{-12}$ m^2/N; $s_{33}^E = 12.45 \times 10^{-12}$ m^2/N; $d_{33} = 190 \times 10^{-12}$ m/V; and $g_{33} = 19.93$ Vm/N. When the GE ceramic is as old as the baseline ceramic, there should be good agreement between the dielectric constant, coupling coefficient, d constant, and g constant. The major difference will be between the elastic compliance constants. The GE ceramic was initially less compliant than the baseline, and as it ages it will become stiffer.

Measurements on GE Area Adjusted Ceramic Rings

In addition to the baseline-like rings, ceramic rings of three very different compositions and with correspondingly adjusted areas (CR.−11, CR.+6, and CR.+18) were received from GE. The rings were prepared as engineering samples to help validate DAS-7 for the TR-317R transducer. It should not be construed that these engineering samples were representative of what GE would supply to an actual production contractor for the transducer or for the ceramic. They were, as stated, samples to empirically test the DAS-7 concept.

The material composition of the rings was identified by GE as V, 190, and 210 series materials. The V material is a Type III ceramic; the 190 and 210 materials are a lead zirconate-titanate composition halfway between Type I and Type III.

The rings were prepared by GE so that all compositions would have an average d_{33} of 198×10^{-12} m/V. However, the dielectric constants of the materials are different. Therefore, the cross-sectional area of the rings was adjusted so that nominal capacitance was approximately the same regardless of the composition (~1625 pF). GE provided 32 rings of V-series material with a cross-sectional area 18% *greater* than baseline; 43 rings of 190-series material with an area 6% *greater* than baseline; and 32 rings of 210-series material with an area 11% *less* than baseline. In all cases, the area adjustment was made at the i.d. of the rings. The o.d. of all the rings is the same as the o.d. of the baseline.

The difference in area of the V- and 210-series rings compared to the baseline is considerably more than the ±6.0% area adjustment allowed by STRIP specification. As previously stated, this radical departure from the baseline formulation was deliberately made to establish confidence in DAS-7.

Since the subject ceramic rings were engineering samples and two of the lots were not a Type III material, high-field $\Delta C/C$ and corona measurements were not made. Individual ring resonance measurements were made, and the critical parameters were computed from the data and the equations in Ref. 10.

Table 9 (rows 1 and 2) is a comparison of the mean value ring parameters per lot determined by the resonance methods at NRL-USRD and the parameter determined at GE for the V-series rings. Good agreement exists between the measurements. To compute the parameters shown in the table, the following lot mean value data were used for each ring:

o.d.	3.37 in.
wall thickness	0.452 in.
height	0.550 in.
density	7.81×10^3 kg/m^3.

Table 9 also shows (row 3) the ring parameters (mean value) of 296 baseline rings 450 days after polarization. Row 4 of Table 9 shows the ring parameters of the GE material projected to the same age as the baseline. The projection is based on the assumption of a maximum aging rate of −5.0% for the dielectric constant, −2.0% for the coupling coefficient, and +1.0% for the frequency constant shown in Ref. 11 Type III ceramic.

The data in Table 9 indicate characteristics about the V material that are necessary for the DAS-7 to give the desired results. First, the dielectric constant is lower than baseline, and the increase in area has brought the capacitance to a value within specification. Second, since the d_{33} virtually matches the baseline as DAS-7 requires, then the g_{33} should be greater than baseline, and this is the case.

Table 10 (rows 1 and 2) are comparisons of NRL-USRD and GE measurements for the 190 series rings. Row 3 shows the old baseline values, and row 4 shows the projected values 450 days after polarization. The latter is based on the aging rates assumed for the V material. Note that the same relationship exists in the 190-series parameters between the dielectric constant-capacitance area and the d_{33}-g_{33} that exists in the V-series parameters. To compute the parameters shown in the table, the following lot mean values were used for each ring:

o.d.	3.37 in.
wall thickness	0.395 in.
height	0.550 in.
density	7.81×10^3 kg/m^3.

Table 9 — Comparison of URSD and GE Ring Parameters Data on V Composition Ceramic Rings (CR. +18%) and Comparison of Time-projected V Parameters with Old Baseline Data

	C_T (pF)	K_{33}^T	k_{33}	s_{33}^D (10^{-12}m^2/N)	s_{33}^E (10^{-12}m^2/N)	d_{33} (10^{-12} m/V)	g_{33} (10^{-3}Vn/N)
USRD Mean Values 69 days after polarization (32 V rings)	1663	982	0.577	9.26	13.88	200	23.1
GE mean values 46 days after polarization (32 V rings)	1662	981	0.574	9.31	13.89	199	23.0
Old baseline mean values 450 days after polarization (296 Gulton rings)	1539 *	1077	0.551	8.66	12.45	190	19.9
GE V ring parameters projected to an age 450 days after polarization	1605	948	0.568	9.25	13.65	192	22.9

*The baseline (production TR-317) capacitance specification is 1550 ±150 pF.

Table 10 — Comparison of USRD and GE Ring Parameter Data on 190 Composition Ceramic Rings (CR. +6%) and Comparison of Time-projected 190 Parameters with Old Baseline Data

	C_T (pF)	K_{33}^T	k_{33}	s_{33}^D (10^{-12} m^2/N)	s_{33}^E (10^{-12} m^2/N)	d_{33} (10^{-12} m/V)	g_{33} (10^{-3} Vn/N)
USRD mean values 42 days after polarization (42 ea 190 rings)	1671	1107	0.553	9.17	13.22	199	20.3
GE mean values 20 days after polarization (42 ea 190 rings)	1675	1109	0.552	9.23	13.26	199	20.3
Old baseline mean values from Table 2 450 days old (296 Gulton rings)	1539 *	1077	0.551	8.66	12.45	190	19.9
GE 190 ring parameters projected to an ange 450 days after polarization	1581	1048	0.542	8.99	12.73	186	20.1

Table 11 (rows 1 and 2) are comparisons of NRL-USRD and GE values for the 210-series rings; row 3 indicates the baseline values, and row 4 shows the projected values at the same aging rates previously assumed. The projected parameters do not show as good a d_{33} to baseline match as in the other cases but do show the proper relationships that are necessary for DAS-7. In this case, the dielectric constant-capacitance area and the d_{33}, g_{33} relationship is opposite that of the V and 190 ceramic: $K_{33}^T > K_{33}^T$ baseline, $C \sim C$ baseline, area < area baseline, and $g_{33} < g_{33}$ baseline. To compute the parameters shown in Table 11, the following low mean value data were used for each ring:

o.d.	3.37 in.
wall thickness	0.325 in.
height	0.550 in.
density	7.81×10^3 kg/m^3.

In summary, the rings from all three GE ceramic compositions were shown to have parameters which, in relation to their area adjustment, complied with the requirements of DAS-7.

Table 11 — Comparison of USRD and GE Ring Parameter Data on 210 Composition Ceramic Rings (CR. −11%) and Comparison of Time-projected 210 Parameters with Baseline Data

	C_T (pF)	K_{33}^T	k_{33}	s_{33}^D (10^{-12} m^2/N)	s_{33}^E (10^{-12} m^2/N)	d_{33} (10^{-12} m/V)	g_{33} (10^{-3} Vn/N)
USRD mean values 41 days after polarization (32 ea 210 rings)	1629	1282	0.532	8.49	11.85	195	17.2
GE mean values 25 days after polarization (32 ea 210 rings)	1638	1288	0.531	8.54	11.89	195	17.1
Old baseline mean values 450 days after polarization (296 Gulton rings)	1539	1077	0.551	8.66	12.45	190	19.9
GE 210 ring parameters projected to an age 450 days after polarization	1539	1215	0.521	8.32	11.41	182	17.0

CSA Parameter Determination for the Radical DAS-7 Experiment

For the CSAs made from the four different GE ceramics, the parameters were determined from resonance measurements on a stressed mass-loaded stack (dumbbell) by using a standard parameter search routine [1]. Table 12 presents the results. Table 12 uses CR.+0 as the reference for the other three adjusted ceramics. (Recall that for CR.+0 the area and thickness are the same as baseline). Although the actual baseline values are not shown, CR.+0 had parameter values very close to the old baseline values.

Table 12 — CSA Dumbbell and Seaducer—Determined DAS—7 Parameters

Ceramic Stack	d_{33} (m/V) (× 10)	(%)	C_T (Farad) (× 10)	(%)	C_c' (m/N) (× 10)	(%)	G (m/N^2) (× 10)	(%)
CR. +0	210.6	0	15572	0	495.6	0	1.35	0
CR. −11	206.4	−2.0	16068	3.2	582.7	17.6	1.28	−5.2
CR. +6	213.3	1.3	16852	8.2	499.2	0.7	1.27	−5.9
CR. +18	218.9	3.9	16720	7.4	424.4	−14.4	1.31	−3.0

Table 12 shows that the largest deviation of d_{33_s} from the CR.+0 value is 3.9%, which occurs on CR.+18. Because only a few rings of any one type were constructed, it was believed that the process could be controlled so that for a larger sample the mean value of d_{33_s} for a set of rings would be within ±2% of the baseline value.

Table 12 also shows that the largest deviation of C_{T_s} from the CR.+0 value is 8.2%, which occurs on CR.+6. A second iteration where ceramic area was further adjusted could have reduced this deviation.

Table 12 lists the computed open-circuit compliance C_{cs}'. Notice that, as expected, this compliance is larger for smaller ceramic areas and smaller for the larger ceramic areas. Similar statements hold for the short-circuit compliance C_{cs}.

Table 12 also lists a quantity G defined as

$$G_s \equiv g_{33_s} \ell / A . \tag{36}$$

Since $g_{33_s} = d_{33_s}/\epsilon^T_{33_s}$ and $C_{T_s} = N A \epsilon^T_{33_s}/\ell$, the following equation for G holds:

$$G_s = d_{33_s}/C_{T_s} . \tag{37}$$

Therefore, application of DAS-7 (which adjusts d_{33_s} and C_{T_s} to baseline values) should automatically adjust G_s to be equal to the baseline value. This fact is used in the next subsection.

Verification from Dumbbell Experiments

Figure 8 shows a plot of input impedance ($|Z_{in}|$) vs frequency for each of the four CSAs, installed one at a time in the dumbbell assembly. Notice that since no fiberglass tuning ring (FTR) was used in the dumbbells to account for the different CSA compliances, the anti-resonance frequencies and resonance frequencies for the different CSAs do not match. At a given low frequency, the capacitance C_{T_s}' is inversely proportional to $|Z_{in}|$. A comparison of C_{T_s} (from Table 12) and $|Z_{in}|$ at low frequencies shows consistency.

Even though in the dumbbell experiments the FTR was not adjusted as required by DAS-7, Eq. (17) shows that for frequencies such that $\omega << \omega_m$ (that is, well below the resonance for V/E in air), V/E in air should be proportional to d_{33_s}. To check this SGM prediction, a photonic sensor technique was used to measure V/E in air on the dumbbell. Figure 9 plots the results. Within the

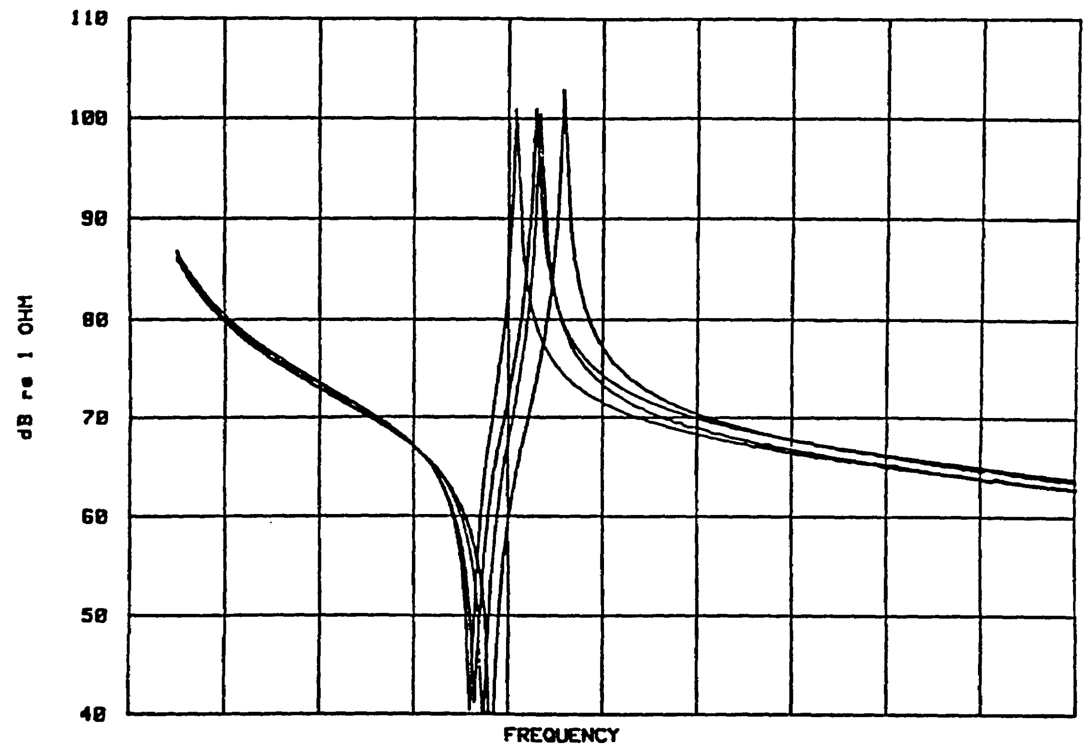

Fig. 8 — Impedance vs frequency for the four GE CSAs, CR.+0, CR.−11, CR.+6, and CR.+18, installed in the same dumbbell assembly

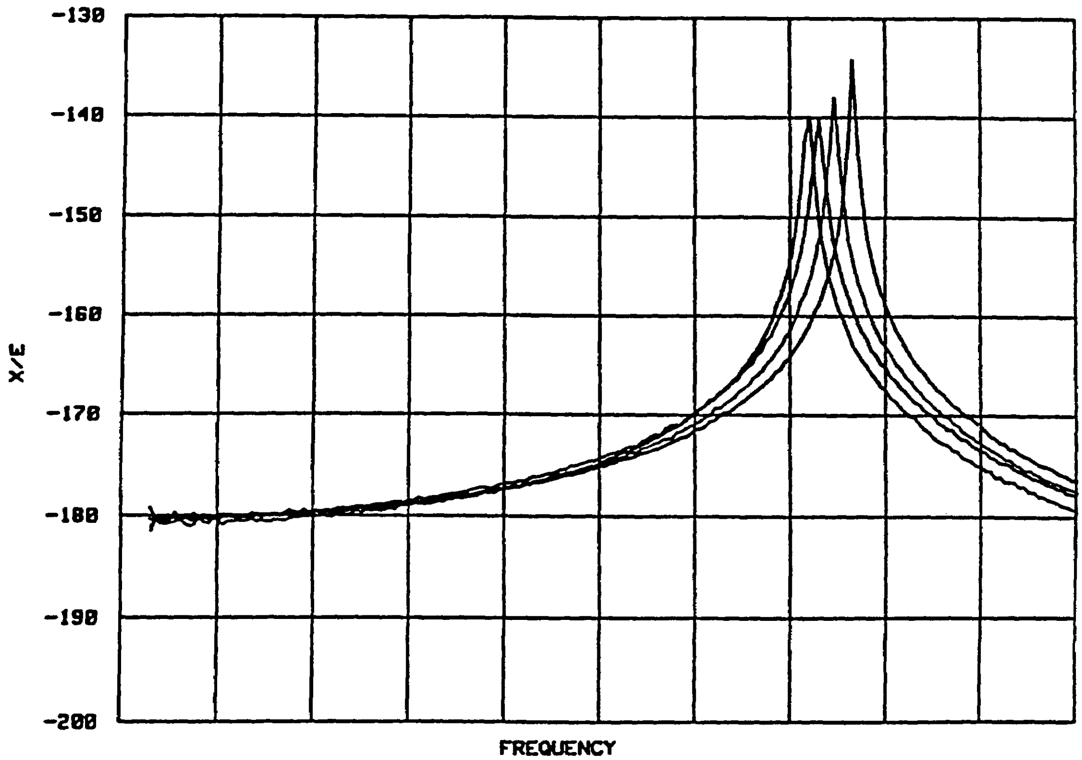

Fig. 9 — Velocity (Displacement)/Volt (V/E) in-air, measured by a photonic sensor, for the four GE CSAs, CR.+0, CR.−11, CR.+6, and CR.+18 installed in a dumbbell assembly, untuned

accuracy of the measurements, results in Fig. 9 are consistent with those of Table 12. For example, according to Table 12, CR.-11 has the lowest value of d_{33}, and in Fig. 9, CR.-11 also has the lowest value of V/E in air at frequencies below ω_m.

Incidentally, this is a convenient time to point out that at or near resonance *in-air* the SGM does not apply because the SGM neglects losses in the CSA. In the dumbbell operating in air near resonance, the CSA losses, although considered modest, are essentially the only dumbbell losses and thus are all that prohibit the impossible condition of an infinite velocity. Therefore, the CSA losses become the controlling factor near a resonance of the dumbbell operating in air.

A situation similar to that for V/E in air holds for V/I in air. Equation (18) shows that V/I in air is proportional to $G = g_{33}\ell_c/A_c$ for frequencies well below ω_n (that is, well below the resonance for V/I in air). Furthermore, Eqs. (36) and (37) show that when, as in DAS-7, d_{33} and C_T have been adjusted to the baseline values, then G is automatically adjusted to the baseline value. To check these SGM prediction, the V/I in air was measured and the results plotted in Fig. 10. The SGM predictions are confirmed since the V/I in air for $\omega << \omega_n$ are nearly the same for all four CSAs. Actually, since DAS-7 was not executed perfectly, Table 12 shows that the values of G for CR.$-$11, CR.+6, and CR.+18 are all slightly lower than for CR.+0. Figure 10 results likewise show that CR.+0 has the highest value of V/I in air below ω_m.

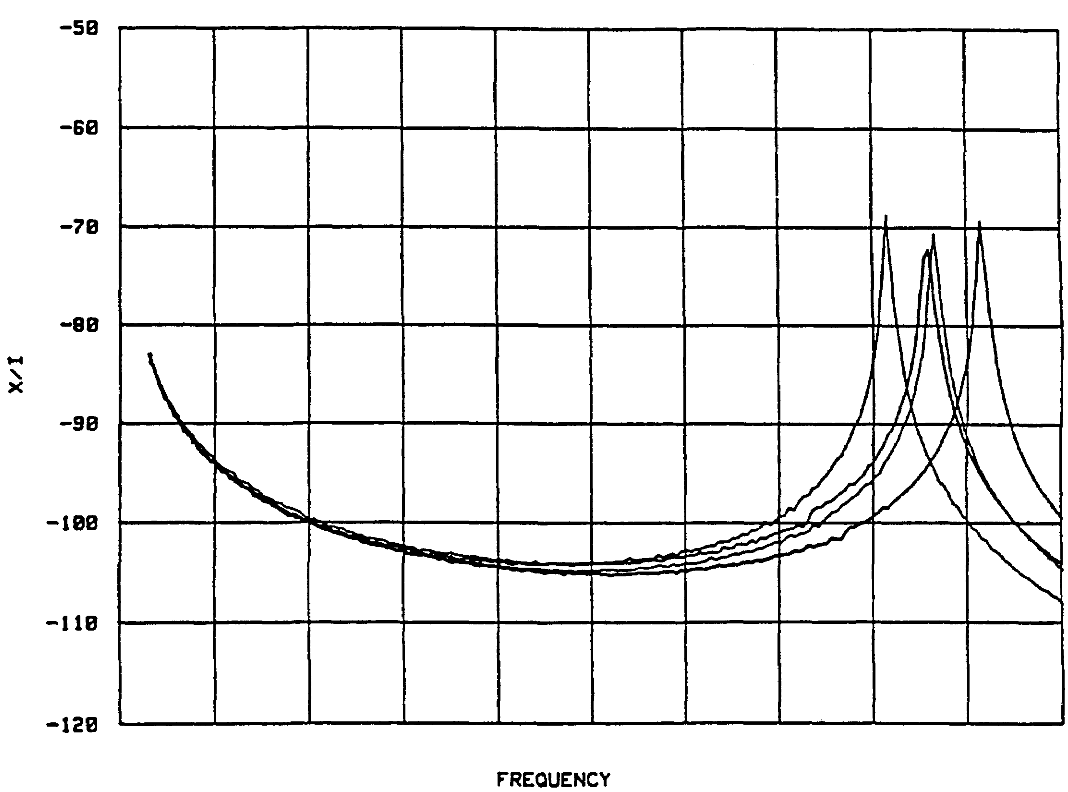

Fig. 10 — Velocity (Displacement)/Ampere (V/I) in-air, measured by a photonic sensor, for the four GE CSAs, CR.+0, CR.$-$11, CR.+6, and CR.+18 installed in a dumbbell assembly, untuned

Verification from Transducer In-Air Experiments

The next step in the experimental test of DAS-7 was to determine the correct FTR for each of the four CSAs to satisfy Step 3(a) or 3(b) of DAS-7, i.e., to adjust $(C_F + C_c)$ or $(C_F + C_c')$ to be equal to the baseline value. This was done by finding the FTR that would adjust either ω_m or ω_n to be equal to the baseline value when used with a given CSA in the actual transducer. Actually, the adjustment was made on ω_n. With ω_n adjusted, all three steps of DAS-7 were completed. Thus, the performance of the transducer in-air or in-water should be the same for all four CSAs and the same as for the baseline CSA.

As a first test of this prediction, the $|Z_{\text{in}}|$ in air was measured and plotted as shown in Fig. 11. As predicted the four curves are nearly overlays. For example, although only ω_n was adjusted with the FTR to match the baseline value, ω_m has automatically been made equal to the baseline value.

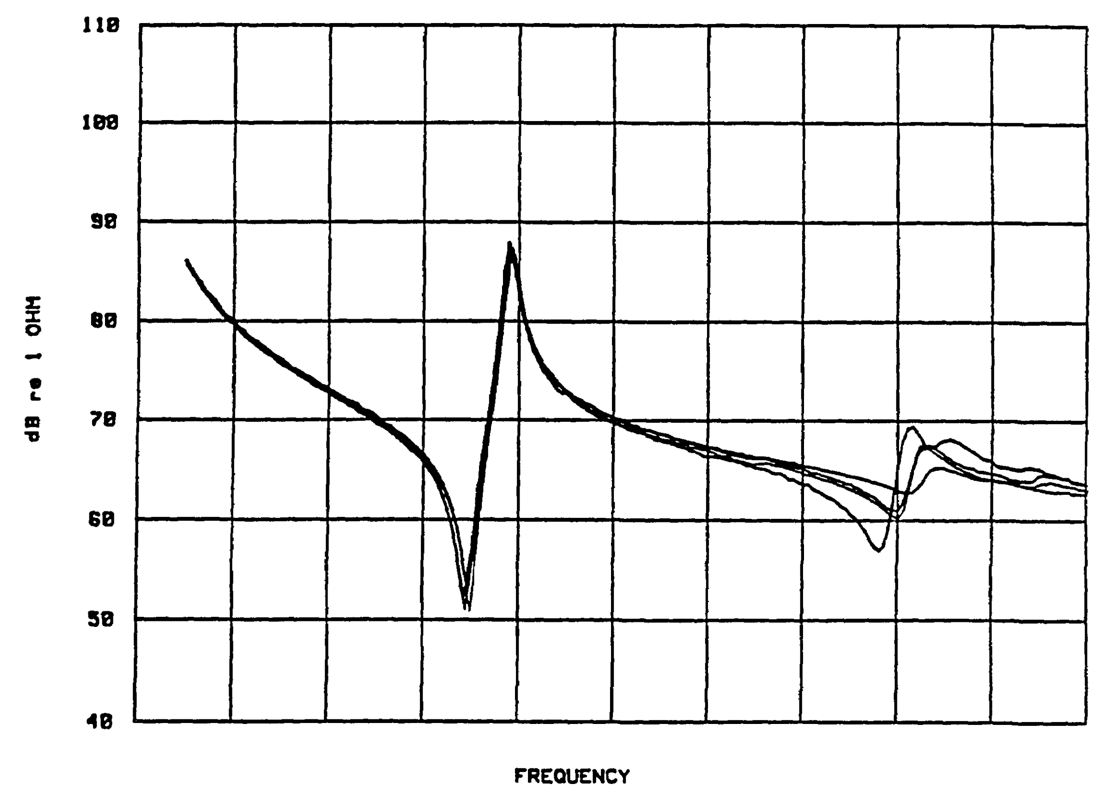

Fig. 11 — Impedance magnitude in-air for the four GE CSAs, CR.+0 CR.−11, CR.+6, and CR.+18, in a transducer, tuned with a fiberglass tuning ring (FTR)

Note that at a certain higher frequency region well above resonance there are some differences in $|Z_{\text{in}}|$ for the four CSAs installed in the transducer. Since this is above the frequency range for which this particular transducer was designed, these differences were not investigated. Although ideally the four CSAs would have been installed one at a time in the same transducer, funding and time constraints did not permit this. Possible differences in the four transducers actually used may account for some of the differences in this higher frequency region. Also, the transducer has a flexing radiating head resonance near the higher frequency region. It is possible that the different ceramic areas of the four CSAs affected this flexural resonance differently. In this regard, it is interesting to note that the nearer the ceramic area is to baseline, the more exact is the fit of the curves in the vicinity of the higher frequency region to the reference curve for the CSA using the baseline area (CR. +0). For example, near the flexing head resonance, CR. +6 results are almost identical to CR. +0, while CR. +18 results are the most unlike CR. +0.

There are two further checks of the SGM predictions. Figure 12 shows a plot of V/E in air for the radiating face of the transducer, and Fig. 13 shows a plot of V/I in air for the radiating face of the transducer. The results are considered excellent confirmation of the validity of the SGM in general and DAS-7 in particular. Further adjustment of the FTR thickness could have matched the frequencies ω_m and ω_n even better. Also, some slight differences not accounted for by the fact that DAS-7 was not carried out exactly may be because four different transducers of the same design were used in the four experiments.

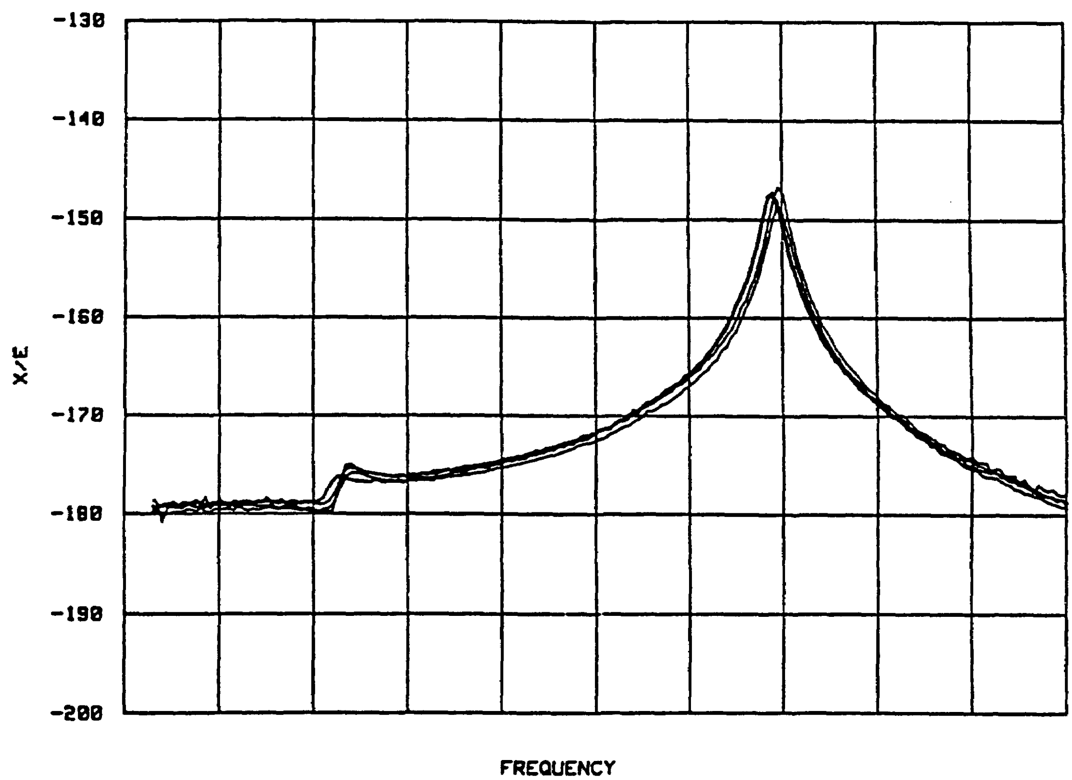

Fig. 12 — Velocity (Displacement)/Volt (V/E) of the four GS CSAs installed in a transducer and measured in-air at the radiating face of the transducer by a photonic sensor

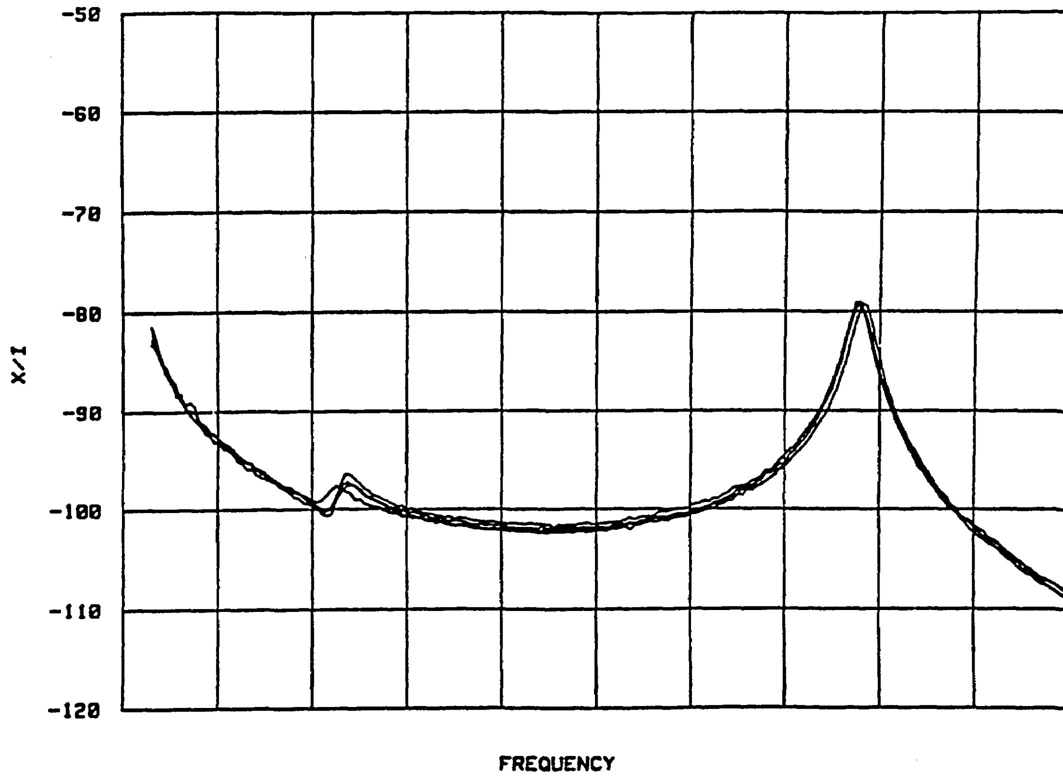

Fig. 13 — Velocity (Displacemnt)/Ampere (V/I) of the four GS CSAs installed in a transducer and measured in-air at the radiating face of the transducer by a photonic sensor

Verification from Transducer In-Water Experiments

The last and perhaps most conclusive step in the experimental validation of the SGM in general and DAS-7 in particular was to test the four transducers containing the four different CSAs in water in the free field. This was done, and the results are considered excellent. The results for the most radical departure from baseline ceramic, namely CR.+18, are compared to the ceramic most like baseline, namely CR.+0. Figure 14 shows the transmit voltage response comparison, and Fig. 15 shows the open-circuit receive response. Even for the radical CR.+18 departure from baseline ceramic, the electroacoustic performance of the baseline CSA has been duplicated. From these results, as well as other experiments and the comparisons with more elaborate predictive models, it was concluded that SGM (and thus DAS-7) is valid for those longitudinal vibrator transducers for which the simplifying assumptions hold.

New Baseline Parameters

In previous sections of this report the term "old baseline" has been used in reference to baseline ceramic parameters. This is because the target ceramic parameters corresponded to early TR-317 production. In later production the parameters changed, and NAVSEA stipulated that the ceramic parameters for the TR-317R match the ceramic parameters of the TR-317 transducer then currently in production (as of July 1984). Accordingly, 50 EDO Western (Gulton) rings (five 10-ring subsets)

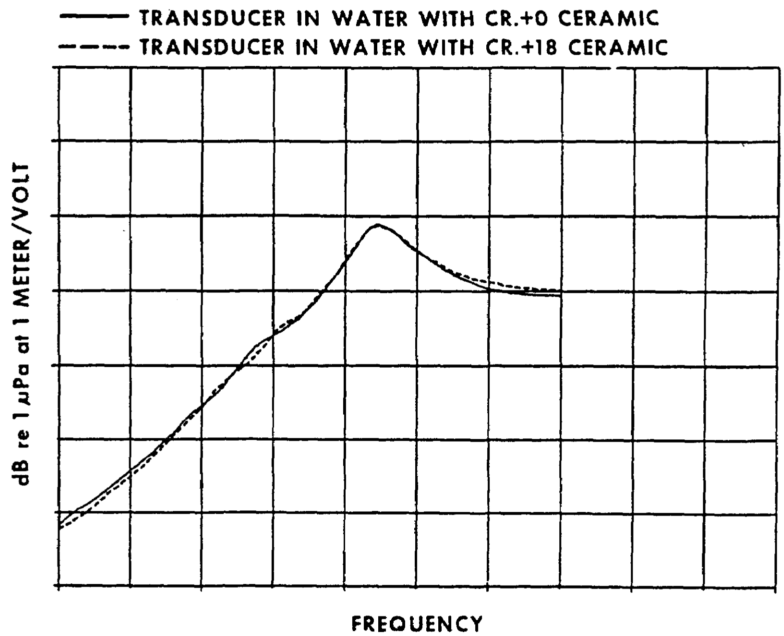

Fig. 14 — Comparison of Transmit Voltage Response (TVR), single element in a free-field, of the transducers with GE CSAs CR. +0 and CR. + 18

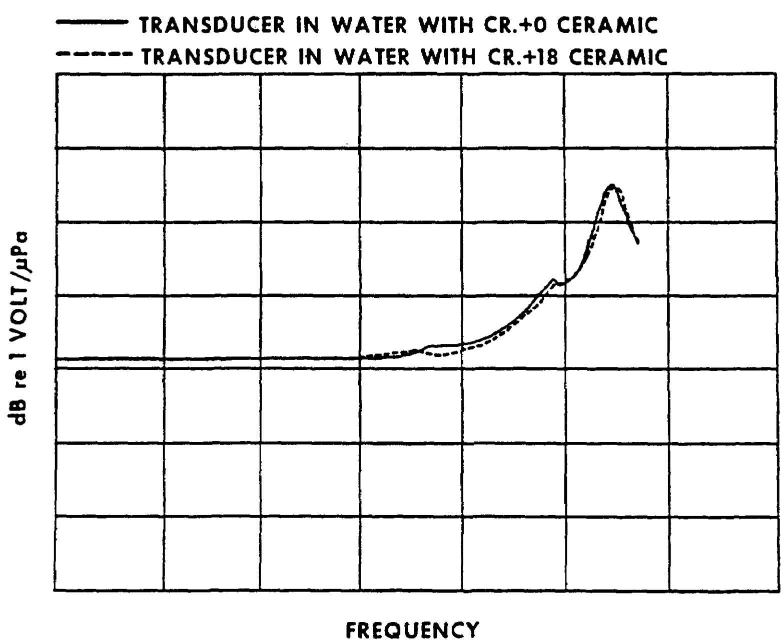

Fig. 15 — Free Field Voltage Sensitivity (FFVS) of transducers with GE CSAs CR. +0 and CR. + 18

were obtained from the Raytheon TR-317 production line with the stipulation that they have the following characteristics:

- The distribution of parameters for the 50 rings must be representative of the distribution of the population in current use.
- The mean value of the characteristics of the rings must be equal to the mean value of the population.

From these rings, new baseline material and ring parameters were determined by the MDRM and by the classical method. The piezoelectric constant d_{33} was also measured on two different d_{33} meters.

Table 13 first shows the material parameters (mean value with standard deviation) computed by the MDRM for the 50 rings 74 days after polarization, and then shows the ring (geometry-dependent) parameters computed by the classical method. Notice in the table the large differences between the material d_{33} of the rings (MDRM) and the d_{33} by the classical method; this glaringly emphasizes why MDRM was developed.

Table 13 — New Baseline Ceramic Parameters, 74 days After Polarization; Mean Value and Standard Deviation for a Popuation of 50 EDO Rings From the Raytheon TR-317B Production Line, Determined by the Modal Decoupling Resonance Method (MDRM) and by the Classical Method [9]

K_{33}^T	d_{33} (10^{-12} m/V)	g_{33} (10^{-3} Vm/N)	s_{33}^D (10^{-12} m^2/N)	s_{33}^E (10^{-12} m^2/N)	k_{33}
Parameters by the Modal Decoupling Resonance Method					
χ 1103.8	244.4	25.0	7.564	13.68	0.668
s 10.7	005.3	0.43	0.127	—	—
Ring Parameters by the Classical Method					
χ 1106.3	22.1	22.6	8.16	13.15	0.616
S 10.3	04.0	0.33	0.10	—	—

TR-317R CSAs Using Honeywell Rings

Based on the above-described success for radical departures from baseline-type ceramic formulations and large area adjustments, the second test of DAS-7 was planned only to be a straightforward demonstration that yet another ceramic ring vendor could successfully produce TR-317R baseline-equivalent piezoelectric ceramic components. However, these Honeywell rings were urgently needed by NWSC/Crane to construct CSAs for use in a STRIP 5 × 5 array experiment [12,13]. Fortunately, success also made it reasonable to fabricate the second-iteration ring (as soon as it had been shown that the 50 first-iteration rings met rings parameter requirements and before these first-iteration rings had been tested in CSAs). This accelerated procedure was followed and was completely successful in meeting all requirements, including the CSA dynamic tester (CDYT) and transducer requirements.

Honeywell was contracted to set aside a powder lot of sufficient quantity to make a minimum of 550 rings. From this powder lot a first-iteration batch of approximately 50 rings was supplied to NRL-USRD. For the first-iteration rings, DAS-7 was exercised with the requirement that the mean value of ring free capacitance and d_{33} match the baseline within $\pm 2\%$. After success with the first-iteration, the remaining 500 second-iteration rings were fabricated.

By the time the Honeywell contract was awarded, the TR-317 production contract had changed ceramic parameters; these changed parameters are referred to as "new baseline parameters." As noted, STRIP was instructed to determine and use the new baseline ceramic parameters for all the remaining TR-317R tasks, including the Honeywell contract.

The first iteration of Honeywell TR-317R ceramic rings was received and evaluated during the first quarter of FY85 [14].

Table 14 shows a comparison between the first-iteration Honeywell ceramic parameters and the new baseline ceramic parameters. Comparison of all the parameters to the baseline is very favorable. It should be noted that Honeywell achieved this result with no area adjustment.

Based only on the first-iteration ring data, Honeywell was given the approval to fabricate the remaining 500 rings from the powder lot. Also four TR-317R CSAs were fabricated from first-iteration Honeywell ceramic rings and sent to NOSC for evaluation in CDYTs and experimental transducers (See Ref. 15, first-iteration stacks in dumbbells and CDYTs). This evaluation was needed as early confirmation that the Honeywell rings would indeed meet all CSA requirements.

The second-iteration rings were received from Honeywell in the second quarter of FY85 and were evaluated [16]. Although there was a difference in age of rings at the time of measurements, the second-iteration rings compared favorably with the baseline. The ring measured data and piezoelectric parameters (material and ring) are also shown in Table 14.

An algorithm (USRD STACKS program) was developed to sort the 500 rings into ten ring sets based on the d_{33}-free capacitance selection specified in NAVSEA Dwg. No. 5516940. The 50 stack sets had a mean value free capacitance of 15,649 pF with a standard deviation of 16.1 pF and a mean value d_{33} of 252.5×10^{-12} m/V, with a standard deviation of 0.4×10^{-12}. The minimum to maximum range of capacitance for the 50 sets was 15,612.8 to 15,688.5 pF or 0.48%; for d_{33}, it was 251.6×10^{-12} to 253.9×10^{-12} or 0.91%.

If an aging rate of -3.24% per time decade (the mean value aging rate determined from 11 first-iteration rings) is applied to these mean values, the free capacitance mean value would be 1550.9 pF at 100 days and the d_{33} would be 250.2×10^{-12}. The projected free capacitance of the sets was well within the requirements of NAVSEA Dwg. No. 5516940 ($C_T = C_{Tb} \pm 2\%$), and the d_{33} was just at the upper limit ($d_{33} = d_{33b} \pm 2.0\%$). These results were considered excellent for the free capacitance and good for the d_{33} because every ring from a small population was included in the stack sets.

From the 50 sets, four were selected for consolidation into CSAs to evaluate the second-iteration ceramic in dumbbells and experimental test-bed transducers (ETs) at NOSC. Five sets of rings were selected for aging studies to better determine the aging rates of the Honeywell ceramic (aging rates were previously determined on 11 first-iteration rings). The remaining 41 sets were shipped to the

Table 14 — Comparison of Honeywell TR-317R Ring Measured Data and Piezoelectric Parameters (Material and Ring) for Baseline and the First- and Second-iteration Honeywell Rings

Measured Data — Mean Value and Standard Deviation							
		f_{m1} (kHz)	f_{n1} (kHz)	f_{m2} (kHz)	f_{n2} (kHz)	C_T @ 1 kHz (pF)	m (kg)
New baseline	$\bar{x}$	14.6457	15.5285	117.1315	143.3891	1563.9	0.2372
(74 days old)	s	0.0468	0.0627	0.2988	0.8168	10.7	0.0009
Honeywell 1st iteration 51 rings	$\bar{x}$	14.4881	15.2859	115.4552	142.3378	1578.0	0.2344
(39 days old)	s	0.0098	0.0219	0.1503	0.1583	6.2	0.0004
Honeywell 2nd iteration, 500 rings	$\bar{x}$	14.4824	15.301	115.3937	142.4636	1564.9	0.23371
(53 days old)	s	0.0534	0.034	0.2968	0.2536	23	0.0024

Material Parameters by MDRM — Mean Value and Standard Deviation							
	K_{33}^T	s_{33}^D	s_{33}^E	k_{33}	g_{33}	d_{33}	C_c'
New baseline	1105.6	7.562	13.625	0.667	24.9	243.6	47.366
$\bar{\rho}$ = 7589.9	10.2	0.018	0.163	0.009	0.4	5.1	
Honeywell 1st iteration	1109.7	7.833	14.330	0.673	25.7	252.7	48.799
$\bar{\rho}$ = 7491.5	4.1	0.023	0.050	0.002	0.11	1.0	0.022
Honeywell	1098.8	7.826	14.440	0.675	25.9	252.8	48.592
2nd iteration	32.6	0.038	0.298	0.006	0.38	3.6	

Geometry-Dependent Ring Parameters — Mean and Standard Deviation						
	K_{33}^T	$s_{33}^D \times 10^{-12}$	$s_{33}^E \times 10^{-12}$	k_{33}	$g_{33} \times 10^{-3}$	$d_{33} \times 10^{-12}$
New baseline	1106.3	8.160	13.153	0.616	22.6	221.12
	10.3	0.103	0.127	.008	0.33	4.05
Honeywell	1110.4	8.440	13.824	0.624	23.4	230.1
1st iteration	4.2	0.019	0.039	0.001	0.09	0.86
Honeywell	1099.3	8.425	13.843	0.626	23.6	229.6
2nd iteration	32.6	0.030	0.077	0.002	0.46	4.2

Naval Weapons Support Center (NWSC) to give NWSC "hands-on" experience in CSA fabrication and to provide CSAs for transducers that were used in a 5 × 5 array test at Lake Seneca [12, 13].

Evaluation of TR-317R CSAs with Honeywell Rings

The four CSAs fabricated by NRL from Honeywell first-iteration ceramic rings were measured by NOSC in the CDYT. These CSAs met all the CDYT requirements (Appendix A describes CDYT and provides typical CDYT acceptance requirements). Thus, based on success in the radical DAS-7 experiment using GE rings it was concluded that Honeywell had successfully produced baseline-equivalent rings in their first iteration. NRL subsequently fabricated four more CSAs by using Honeywell second-iteration ceramic rings. As expected, these second-iteration CSAs also met the CDYT requirements (see Ref. 17 for second-iteration CSA parameters in dumbbells).

Figure 16 is a comparison of the primary subassembly (a transducer without the auto-transformer) in-air impedance magnitude response of three transducers using first-iteration Honeywell CSAs (labeled Hon-3, Hon-4, and Hon-5) with three transducers using second-iteration Honeywell CSAs (labeled Hon-47, Hon-49, and Hon-50). The primary subassemblies using second-iteration CSAs showed ~20 Hz increase in value of f_n (frequency of maximum impedance in the figure) compared to the primary subassemblies using first-iteration CSAs. This difference could have been eliminated by a finer adjustment of the fiberglass tuning ring thickness. All primary subassemblies met the FSP requirements.

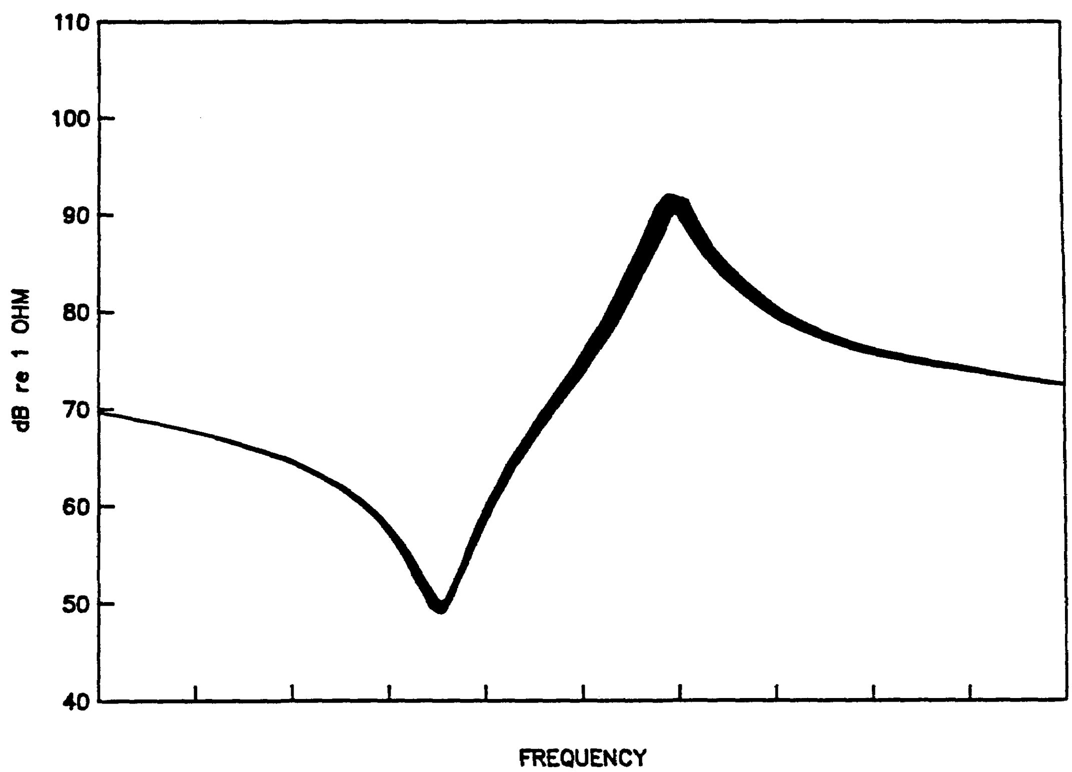

Fig. 16 — In-air impedance magnitude envelope for three transducers using first-iteration Honeywell CSAs and three transducers using second-iteration Honeywell CSAs.

The general conclusion was that Honeywell rings produced CSAs that could meet all FSP requirements. Therefore Honeywell CSAs were used interchangeably with baseline CSAs in the remainder of the STRIP tasks.

TR-317R CSAs Using Channel Rings

A contract was let in FY85 to Channel Industries that contained in the statement of work the kernel of the TR-317R Ceramic Ring Specification found in NAVSEA Dwg. No. 53711-5516940. The contract specified that the ceramic rings must meet the same high field, thermal stability, aging, identification, dimensional, and range of parameter specifications as the TR-317R ceramic. Furthermore, the piezoelectric constant d_{33} would be computed by the Ratio Method (RM).

The contract also required that Channel Industries deliver two iterations of ceramic rings, with a minimum of 35 rings in each iteration. For the first-iteration ceramic rings, the mean value of the delivered population was to have the following characteristics:

$$d_{33} = d_{33b} \pm 4\% \text{ (70 days after polarization)},$$

$$C_T = C_{Tb} \pm 4\% \text{ (70 days after polarization)},$$

where

$$d_{33b} = 243.4 \times 10^{-12} \text{ m/V}$$

and

$$C_{Tb} = 1564 \text{ pF (new baseline values)}.$$

For the second-iteration, the mean value of the delivered population was to be

$$d_{33} = d_{33b} \pm 2\%$$

$$C_T = C_{Tb} \pm 2\%.$$

Evaluation of Channel TR-317R Rings

The first- and second-iteration sets of the new Channel Type III ceramic rings, designated material type C-5804 by Channel, were received and evaluated during the first quarter of FY86 (see Ref. 18 for ceramic ring parameters). The mean value of the population for both iterations was well within the d_{33} and C_T requirements of the contract.

The dielectric constant aging rate for the Channel ceramic was determined from the time-dependent free capacitance data. The aging rates were well within the aging rate requirements of the TR-317R Ceramic Ring Specification. A major concern in the past has been that Channel Type III ceramic did not meet the high-field requirements of DOD-STD-1376A(SH) [19,20]. Therefore, 10 rings were selected at random from both iterations of the Channel ceramic and subjected to high-field tests. The results indicated that the high-field characteristics of the new Channel Type III ceramic was comparable to the baseline TR-317R ceramic rings. The mean value of ΔC_T vs high-field (combined population of 20 rings) was 2.8%; this was well within the high-field requirements of Ref. 11 for Type III material.

In summary, the Channel ceramic at the ring level met the requirements of NAVSEA Dwg. No. 53711-5516940, TR-317R Ceramic Ring Specification. Final acceptability of the ceramic was determined from CSAs tested in dumbbells and ETs. Six CSAs, three from each iteration, were fabricated by NWSC Crane and sent to NOSC for final evaluation.

It should be noted that Channel met the requirements of the ceramic ring specification without an area adjustment. Recall that DAS-7, the heart of the TR-317R ceramic ring specification, allows a ceramic contractor to make a one-time area adjustment up to ±6% if needed to meet the capacitance requirements. Channel did not elect to exercise the option and met the specifications.

Evaluation of CSAs with Channel Rings

Six CSAs were fabricated by NWSC using Channel ceramic rings. Three of the CSAs (1C1, 1C2, and 1C3) used first-iteration Channel rings, and the other three CSAs (2C1, 2C2, and 2C3) used second-iteration Channel rings. Unfortunately there were a number of fabrication flaws in some of these six Channel CSAs. For example, CSA 2C2 contained a ring with reverse polarity. When all information, such as the various fabrication defects and possible measurement errors, was considered, it was decided that the uncertainties associated with these CSAs would tend to invalidate test results with CDYTs and transducers that used these CSAs. Nevertheless, at least one Channel second-iteration CSA, 2C1, met all the CDYT, PSA, and transducer in-water FSP requirements.

No resources were available to correct the fabrication flaws and uncertainties associated with the Channel CSAs. There may have been an example in which the rings met the ring requirement, but the CSAs did not meet the CDYT capacitance requirement. This is not likely, based on the results of the radical DAS-7 experiment reported above. However, even this possibility represents strong justification for requiring that CSAs meet all requirements before the ceramic ingredients lot is considered qualified (for more information on ingredients lot qualification procedure see Appendix D, 3.2.1 Qualification Procedure).

TR-317R CSAs Using Almax Rings from CSA Sample Buys

Baseline-equivalent ceramic rings were also produced by Almax as part of the STRIP TR-317R CSA Sample Buys. It should be noted that Almax elected to make an area adjustment; namely, Almax used an area A that was ~3% greater than the baseline area A_b. These Almax results and many other contribution to perfecting and completing the piezoelectric portions of the TR-317( ) FSP are described in more detail "Piezoelectric Ceramic Reproducibility Sample Production Buys" of Appendix E.

TR-330A Ceramic Components

Paralleling the radical experiment that used GE rings to validate DAS-7 for rings and CSAs for the TR-317R, an experimental test was conducted to determine if DAS-7 would work equally well on a quite different transducer, the TR-330A. This successful experimental verification of DAS-7 applied to TR-330 CSAs is reported next.

A contract was issued to Honeywell to apply DAS-7 in an attempt to produce baseline-equivalent TR-330A ceramic rings. Honeywell conducted three iterations before successfully producing TR-330A baseline-equivalent rings. The first two iterations failed. This was because STRIP had not at that time perfected a method to measure d_{33} for ceramic rings (the MDRM and the RM described previously in this report had not been developed at the time). During the first two iterations, Honeywell attempted to use the Berlincourt d_{33} meter to measure d_{33}. It turned out that the corresponding measurements of d_{33} were erratic. Thus Honeywell had, in essence, a moving target value of d_{33} during the first two iterations (see Refs. 21 and 22 for detailed information of first- and second-iteration rings).

The severity of the d_{33} measurement problem at Honeywell motivated STRIP to accelerate development of the MDRM and RM for determining d_{33}. By the time of the third iteration, STRIP had solved the d_{33} measurement problem. This solution plus the experience from the first two iterations enabled Honeywell to succeed in producing baseline-equivalent ceramic rings in the third iteration.

Evaluation of Third-Iteration Honeywell TR-330A Rings

The third-iteration rings were received and evaluated in March 1985. The ceramic ring parameters were determined by using the MDRM. These parameters and projected 250-day-old values were in agreement with the target baseline values. For example, the target value for d_{33} was 291.1×10^{-12} m/V, and the projected mean value for the third-iteration Honeywell rings was 292.9×10^{-12} m/V. Therefore, at least on a ring material parameter basis, Honeywell succeeded in the third iteration in producing target values for baseline-equivalent TR-330A ceramic rings [23,24] for ring data).

TR-330A CSAs Using Honeywell Rings

NRL-USRD fabricated four CSAs using Honeywell third-iteration TR-330A rings. NOSC evaluated two of these CSAs in the CDYT for the TR-330A. The CDYT results met all requirements. For example, Fig. 17 shows that with the addition of the proper fiberglass tuning rings (0.030-in. thick for the CSA labeled Hon-6 and 0.020-in. thick for the CSA labeled Hon-8) the two third-iteration Honeywell CSAs met the impedance magnitude envelope requirements of the CDYT.

At this point, great confidence had been developed in the CDYT. That is, if a CDYT showed a CSA to met all requirements, that CSA would meet all transducer requirements. It was concluded that in the third iteration Honeywell had succeeded in producing baseline-equivalent ceramic rings in the sense required by DAS-7.

It should also be noted that these results present another example of positive compliance with the ceramic ring-to-CSA rule. Specifically it was shown that when, in a DAS-7 sense, Honeywell produced baseline-equivalent rings, these rings produced baseline-equivalent doubly stressed (radial/circumferential and longitudinal) CSAs.

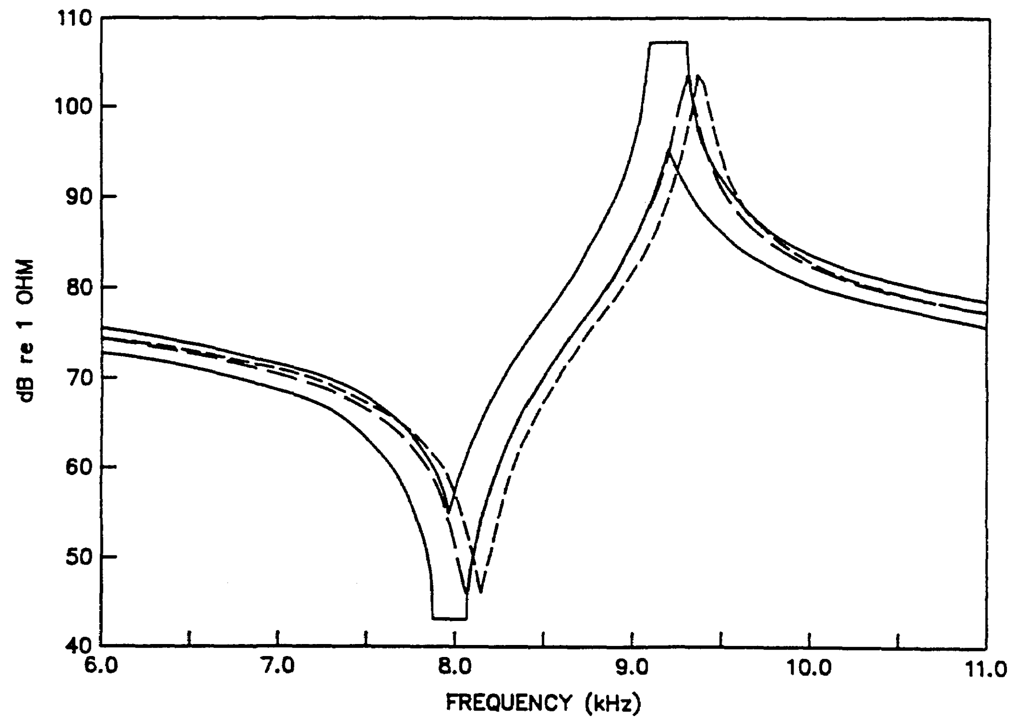

Fig. 17 — In-air impedance magnitude response of two third-iteration Honeywell CSAs. The solid lines form the CDYT acceptance envelope; the short dashed line is CSA Hon-6 and the long dashed line is CSA Hon-8.

SUMMARY

Summary of Experimental Validation Results

The experimental validation results are summarized as follows:

1. DAS-7 and thus the Simplified Guidance Model in general have been experimentally validated for any transducers for which the simplifying assumptions hold. The simplifying assumptions are valid for most Navy longitudinal vibrator transducer elements.

2. Because of item 1, it can be concluded that the CSA Dynamic Tester has been validated as a purely experimental (noncomputational) method to verify that a baseline-equivalent CSA have been produced.

3. The ceramic ring-to-CSA correlation has been shown to hold, even for examples of radical departures from the baseline piezoelectric powder formulation.

4. The Modal Decoupling Resonance Method (MDRM) is the foundational method for determining the piezoelectric ceramic parameters of 33-mode ceramic rings.

5. The Ratio Method of ceramic ring parameter determination has been shown to be robust and to hold for ring geometries similar to those found in the TR-317R and TR-330A transducers, and it is a suitable substitute for MDRM in production.

Summary of Report

The complete STRIP solution to the problem of reproducibility and uniformity has been presented. A new concept in understanding longitudinal vibrators and the ceramic parameters that control the performance has been shown. Improved methods of determining ceramic ring and stack assembly parameters and a noncomputational dynamic test method to certify the performance of a CSA has been presented. The technical solution to the problem of reproducibility has been experimentally validated. A DAS-7 ceramic ring specification has been successfully exercised with all the major domestic ceramic manufacturers and two major foreign manufacturers. Sample Production Buys exercising the TR-317R CSA FSP have been successfully accomplished with Raytheon and Westinghouse.

EPILOGUE

A production contract for TR-317B transducers that required a two-parameter (d_{33} and free capacitance C_T) ceramic ring selection procedure has been competitively awarded to Raytheon. The contractor has elected to use the RM to obtain ceramic parameters with the TR-317( ) parameters as baseline. Also, Raytheon and GE have been competitively awarded contracts to manufacturer TR 317( ) transducers in accordance with the STRIP-developed TR-317R Fabrication Specification Package.

ACKNOWLEDGMENTS

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R.W. Timme	NRL-USRD	STRIP Manager
D.L. Carson	NOSC	TR-317R Product Fabrication Specification
S. Nichols	NOSC	TR-317R Product Fabrication Specification
G. Benthien	NOSC	Math models, MDRM and SGM
A.C. Tims	NRL-USRD	Ceramic measurements, stacks, and specifications
C.M. Ruggiero	NRL-USRD	Computer software and ceramic measurements
K.M. Webman	NUSC	Product in-water performance
T. Peter	NWSC	Drawing package development
S. Thornton	TRI	Product specifications and tests
K. Somers	NOSC	TR-330A product fabrication specification

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23. W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) FY85 First Quarter Progress Report (U)," NRL Memorandum Report 5580, Jan. 1985, pp. 218-220 (Confidential).

24. 24. W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) FY85 Third Quarter Progress Report (U)," NRL Memorandum Report 5685, July 1985, Work Units II.B.1 and IV.B.1 (Confidential).

Appendix A

TR-330A CERAMIC STACK DYNAMIC TEST

This appendix is an excerpt from the TR-330A Test Requirements Specification, NAVSEA Dwg. 53711-5517119 and indicates the scope, configuration, use, and acceptance requirements for a Ceramic Stack Dynamic Test (CDYT). All stop numbers, figures, and references apply to the NAVSEA drawing or drawings in the TR-330A FSP. Pertinent drawings are placed together at end of this appendix.

2.2 DEFINITIONS

2.2.1 Subscripts. The subscripts used are:

a. b = baseline (e.g., F_{nsb} = baseline CSA frequency of maximum impedance)

b. f = fiberglass (e.g., L_f = thickness of fiberglass tuning ring)

c. s = ceramic stack (e.g., f_{ns} = ceramic stack frequency of maximum impedance)

2.2.2 Acronyms. The acronyms used are:

ACRONYM	DEFINITION	PARAGRAPH
CDYT	Ceramic stack dynamic tester	3.2.2
CSA	Ceramic stack assembly	3.2
PSA	Primary subassembly	3.2.4.1.3

2.2.3 Terminology. The following terms and abbreviations are found in the text of this document. The stop number after each definition indicates where the term first appears herein.

TERM	DEFINITION	PARAGRAPH
C'_{cs}	Ceramic stack open-circuit compliance	3.2.4.1
C_T	Low-frequency capacitance ceramic stack in CDYT, C_{Ts}	3.2.4.2.2.5.1
D_T	Low-frequency dissipation factor (tan δ) ceramic stack in CDYT, D_{Ts}	3.2.4.2.2.5.2
f_m	Frequency of minimum impedance ceramic stack in CDYT, f_{ms}	3.2.4.2.2.4
f_n	Frequency of maximum impedance ceramic stack in CDYT, f_{ns}	3.2.4.2.1
Z	Impedance magnitude versus frequency ceramic stack in CDYT, Z_s	3.2.4.2.2.1
Z_m	Impedance magnitude at f_m ceramic stack in CDYT, Z_{ms}	3.2.4.2.2.2
Z_n	Impedance magnitude at f_n ceramic stack in CDYT, Z_{ns}	3.2.4.2.2.3

3.0 TEST REQUIREMENTS AND PROCEDURES

In each section of the following test requirements, certain equipment or test fixtures are mandatory in the performance of the test. This equipment is listed in the Test Equipment Section of each test requirement under the heading "Mandatory" and cannot be changed except by Government approval.

The electronic equipment list in the Test Equipment Section of each test requirement under the heading "Acceptable" indicates the equipment that was used by the Government in the development of the test. A contractor-defined/Government-approved equipment system of equivalent function and equivalent or better accuracy and resolution may be substituted for the equipment specified.

3.2 Ceramic stack assembly (CSA) dynamic test. Refer to 2.2 for definitions.

WARNING: **For safety purposes, the ceramic stack electrical terminals shall be shorted together at all times except when making measurements.**

3.2.1 Test objective. To determine whether the dynamic parameters of a given longitudinally prestressed CSA are within limits.

3.2.2 Sampling plan

3.2.2.1 A production lot shall be all CSAs fabricated in one day using the same personnel, processes and materials, and under the same conditions in compliance with CSA Dwg. No. 53711-5517053.

3.2.2.2 Sampling shall be as follows:

a. One-hundred percent of the qualification CSAs (see Dwg. No. 53711-5517076).

b. One-hundred percent of the CSAs used in first article transducers (see Dwg. No. 53711-5517118).

c. Each production lot of CSAs shall be sampled per MIL-STD-105D, Normal Inspection Level S-2, Single Sampling AQL of 4.0.

d. Two CSAs constructed from each qualified piezoelectric ceramic ingredients lot (see 53711-5517076) shall remain in CDYTs and shall be shipped to the designated Government agency to be used to determine longitudinally prestressed CSA aging characteristics.

3.2.3 Prerequisities. The CSAs shall have been constructed according to 53711-5517053. The CSAs shall contain ceramic rings with an age since poling of no less than 90 days.

3.2.4 Test description. Measurement of CSA dynamic parameter data shall be performed in accordance with the requirements of this paragraph.

3.2.4.1 CSA open circuit compliance. C'_{cs} is determined indirectly by determining tuning ring thickness, L_f, such that 3.2.6 acceptance requirements are met.

3.2.4.1.1 Using a contractor-selected, Government-approved procedure, make an initial selection for the thickness, L_f.

3.2.4.1.2 Using a tuning ring (53711-5517086) of the selected thickness bonded to a rear mass (53711-5517068) install, but do not cement, the CSA in the CDYT (see Fig. 3.2-1). This assembly is henceforth referred to as the CDYT assembly. Bond tuning ring to rear mass in accordance with the procedure defined in 53711-5517043, Sheet 2, Notes 1-6. Note also that a thin layer of grease should be applied to each end of the CSA for better coupling.

3.2.4.1.3 Apply a 4800 ±100 pound force compressive load to the CSA, using a contractor-developed Government-approved procedure.

3.2.4.1.4 Allow the CDYT assembly to stabilize, relative to the compressive load applied in 3.2.4.1.3 test step, for at least 12 days.

NOTE: It has been shown, however, that after only 24 hours it is useful to perform a preliminary culling operation in which CSAs which can clearly never meet the 3.2.6.1 and 3.2.6.2 requirements are identified and rejected. This early detection frees CDYT hardware.

3.2.4.1.5 Place the CDYT assembly in the test fixture (see Fig. 3.2-2).

3.2.4.2 With the CDYT assembly and all instrumentation stabilized to a temperature of 22 ±2.5°C, measure and record data as follows.

3.2.4.2.1 Measure and record f_{ns}.

3.2.4.2.1.1 If 3.2.6.1 and 3.2.6.2 (acceptance requirements) are met, continue measuring and recording data by proceeding to 3.2.4.2.2.

3.2.4.2.1.2 If 3.2.6.1 and 3.2.6.2 (acceptance requirements) are not met, use the following or a Government-approved procedure to select an adjusted L_f such that the acceptance requirements are met:

a. f_{ms} decreases approximately 5.6 Hz per mil increase in L_f,

b. f_{ns} decreases approximately 8.6 Hz per mil increase in L_f.

Estimate the change needed in the selected L_f which should result in meeting the acceptance requirements.

3.2.4.2.1.2.1 If the estimated results indicate that an acceptable tuning ring exists, then select a new tuning ring/rear mass as close as is reasonable to the estimated L_f and proceed as follows.

3.2.4.2.1.2.2 Disassemble the CDYT assembly, remove the initially selected fiberglass tuning ring/rear mass, and reassemble the CDYT assembly with the newly selected fiberglass tuning ring/rear mass. The disassembly-reassembly procedure shall be completed in less than 1 hour.

3.2.4.2.1.2.3 Allow the reassembled CDYT assembly to stabilize for at least 72 hours relative to the compressive load applied in 3.2.4.2.1.2.2.

3.2.4.2.1.2.4 Repeat test steps beginning with 3.2.4.1.5.

3.2.4.2.1.3 If using the procedure of 3.2.4.2.1.2 or a contractor selected procedure, no acceptable tuning ring can be shown to exist, terminate the test, disassemble the CDYT, discard the CSA.

3.2.4.2.2 Measure and record the following:

3.2.4.2.2.1 Z_s from 1000 Hz to 11000 Hz.

3.2.4.2.2.2 Z_{ms}

3.2.4.2.2.3 Z_{ns}

3.2.4.2.2.4 f_{ms}

3.2.4.2.2.5 Use an impedance bridge or analyzer to measure and record the following:

3.2.4.2.2.5.1 C_{Ts} at 1000 ±20 Hz

3.2.4.2.2.5.2 D_{Ts} at 1000 ±20 Hz

3.2.5 <u>Test equipment.</u>

3.2.5.1 <u>Mandatory.</u>

a. CDYTs (as many as needed for scheduling).

b. CDYT Assembly Test Fixture (as many as needed for scheduling).

The test fixture is used to support the CDYT assembly during testing.

3.2.5.2 Acceptable (Equivalent or better equipment may be substituted).

a. HP4192A LF Impedance Analyzer

b. Computer Controller

c. Plotter or Printer

The impedance measurement system configured as shown in Figure 3.2-3 is used to measure Z_s, Z_{ms}, Z_{ns}, f_{ms}, f_{ns}, C_{Ts} and D_{Ts}.

3.2.6 Acceptance requirements.

Each CSA when tested as required in 3.2.4 shall meet acceptance requirements of this paragraph.

3.2.6.1 $f_{ns} = f_{nsb} \pm 100$ Hz where $f_{nsb} = 9110$ Hz.

3.2.6.2 $0.000 \leq L_f \leq 0.050$ inch.

3.2.6.3 $\frac{f_{ns}}{f_{ms}} = \frac{f_{nsb}}{f_{msb}} \pm 1.5\%$ where $\frac{f_{nsb}}{f_{msb}}$ = is determined using the value of f_{ns} (record from successful accomplishment of 3.2.4.2.1) in the following equation:

$$\frac{f_{nsb}}{f_{msb}} = 0.8630 + 3.1395\,(10^{-5})\,f_{ns}$$

3.2.6.4 $20 \log_{10} \left[\frac{Z_{ns}}{Z_{ms}} \right] = 58 \pm 4$ dB

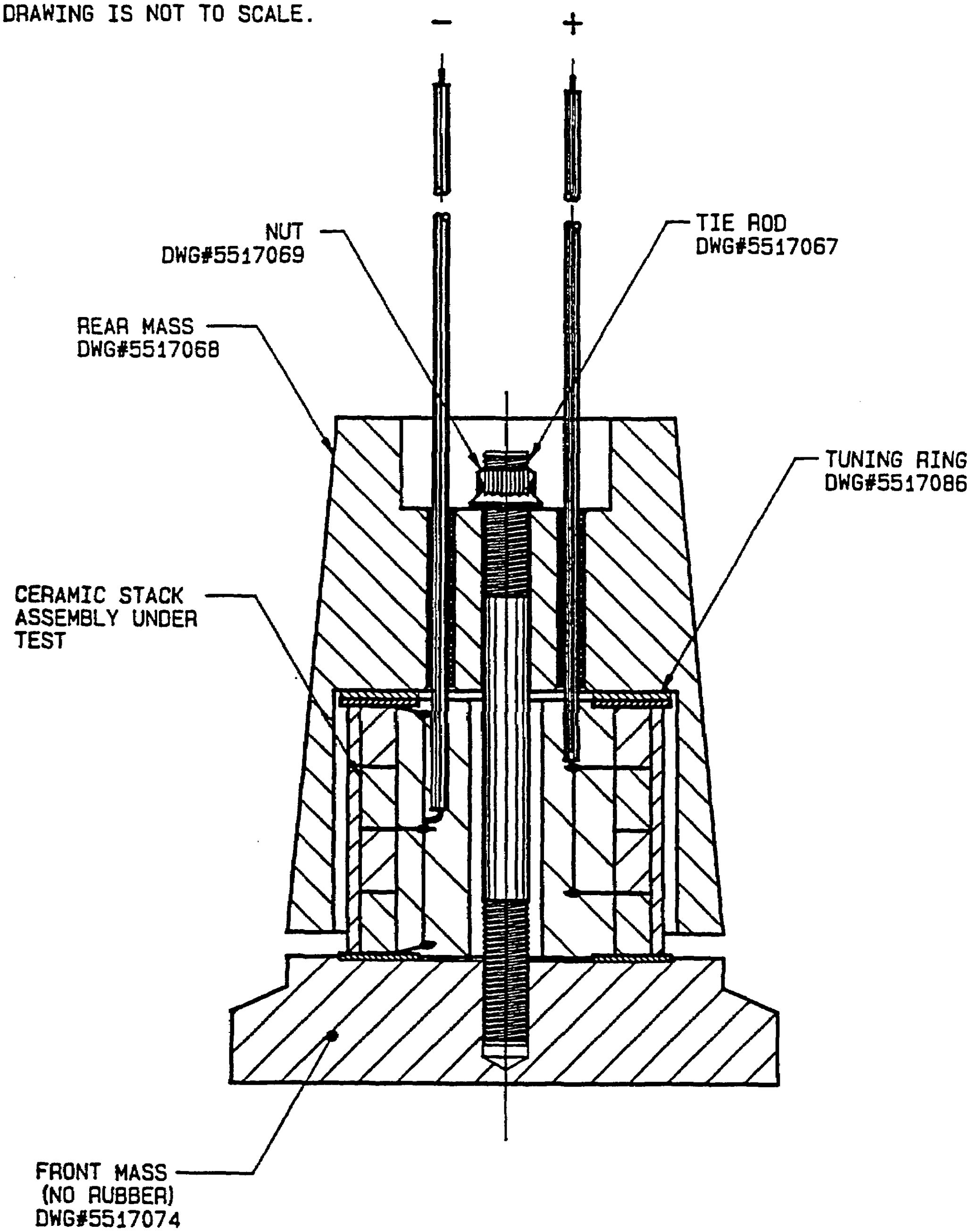
3.2.6.5 $C_{Ts} = C_{Tsb} \pm 5.0\%$ (.207 nanofarads) where $C_{Tsb} = 4.15$ nanofarads

3.2.6.6 D_{Ts} shall be less than 0.006

3.2.6.7 Z_s over the frequency region from 1000 Hz to 11000 Hz shall be within the envelope shown in Figure 3.2-4.

NOTES:

1. DRAWING IS NOT TO SCALE.



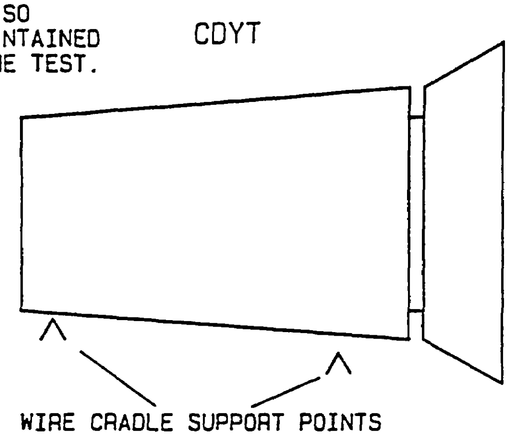
CROSS SECTION VIEW OF CDYT ASSEMBLY
FIGURE 3.2-1

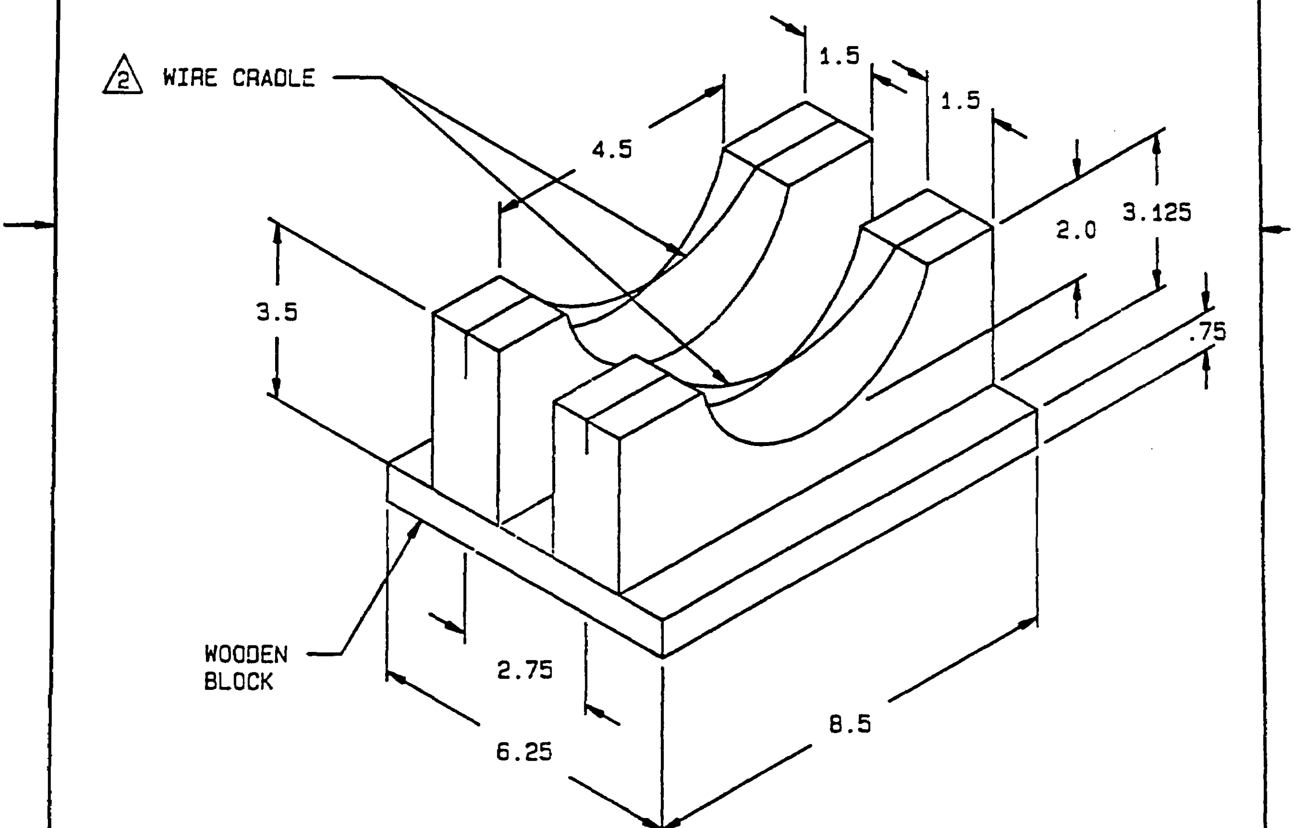
SIZE	FSCM	DWG NO.	REV
A	53711	5517119	
SCALE		SHEET 11	OF 28

NOTES:

1. DRAWING IS NOT TO SCALE.

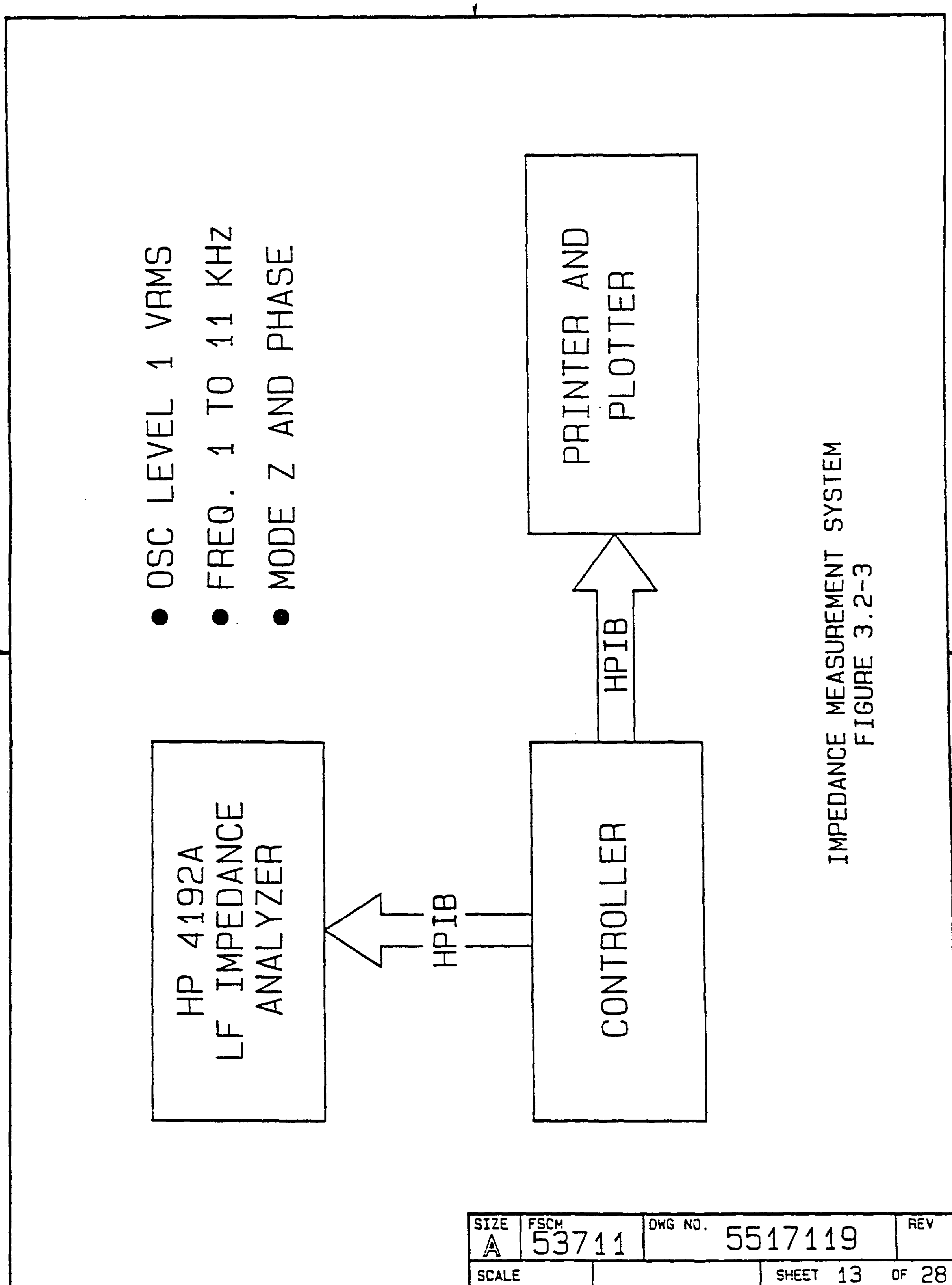
2. ADJUST WIRE TENSION SO THAT THE CDYT IS MAINTAINED HORIZONTAL DURING THE TEST.





CDYT ASSEMBLY TEST FIXTURE
FIGURE 3.2-2

SIZE	FSCM	DWG NO.	REV
A	53711	5517119	
SCALE		SHEET 12	OF 28



IMPEDANCE MEASUREMENT SYSTEM
FIGURE 3.2-3

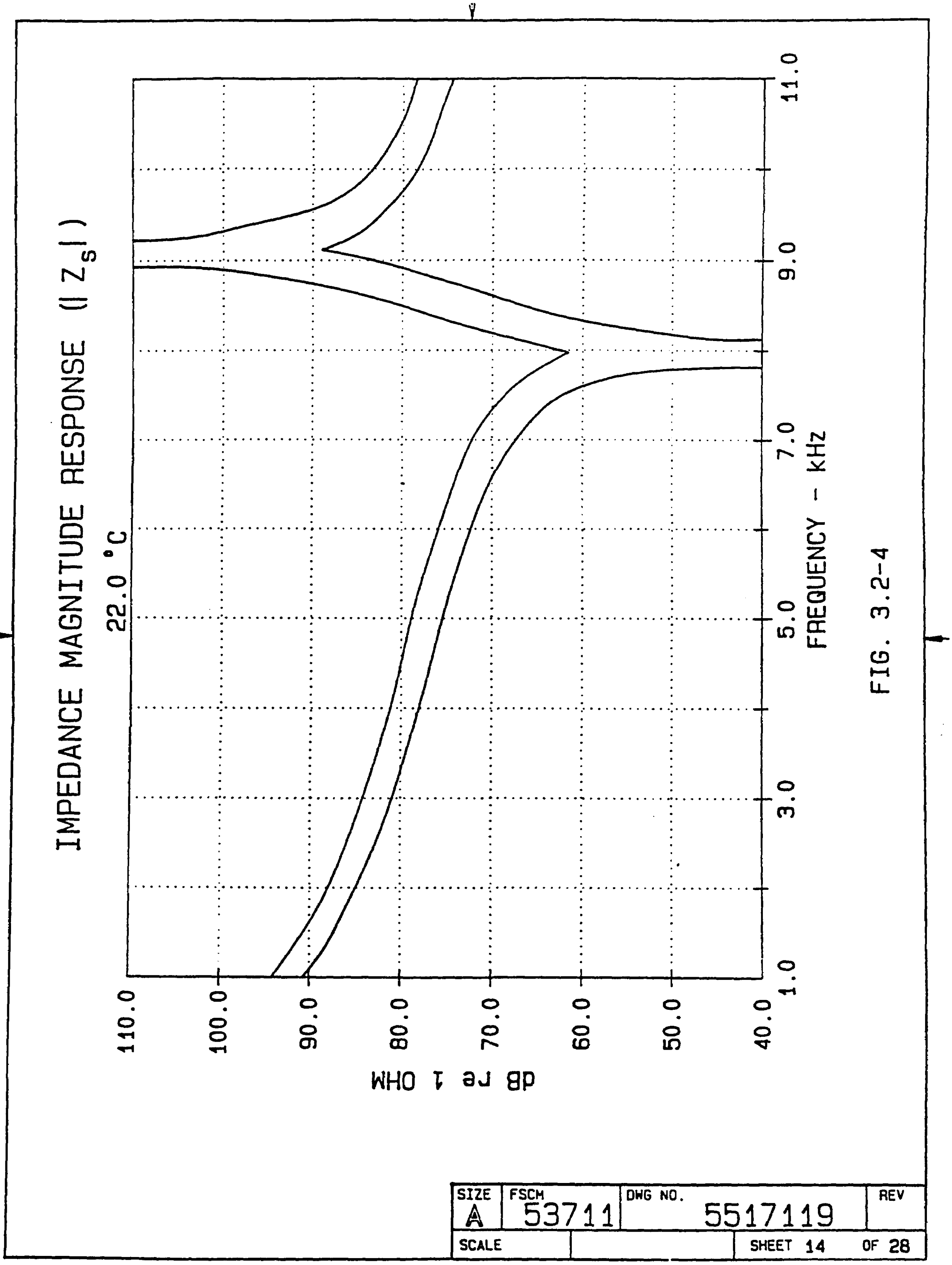

IMPEDANCE MAGNITUDE RESPONSE (| Z_s |)
22.0 °C
dB re 1 OHM
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
1.0
3.0
5.0
7.0
9.0
11.0
FREQUENCY - kHz
SIZE A
FSCM 53711
DWG NO. 5517119
REV
SCALE
SHEET 14 OF 28

FIG. 3.2-4

Appendix B

MODAL DECOUPLING RESONANCE METHOD (MDRM) FOR EARLY TR-330A SPECIFICATION

This appendix is an excerpt from a TR-330A Ceramic Ring Specification that existed early in the development of the TR-330A Fabrication Specification Package (FSP). The following is an example of the Modal Decoupling Resonance Method (MDRM) for determining the piezoelectric parameters of ceramic and notes how the MDRM was applied in the ceramic ring specification. Pertinent drawings are placed together at end of this appendix.

1.0 SCOPE

1.1 This specification establishes the requirements for the piezoelectric ceramic rings for the TR-330A transducer, including the qualification procedure for the material from which the rings are made. The allowable adjustments to meet these requirements are also specified. The symbols used in this section are defined as follows:

1.1.1. Parameters

The ceramic parameters discussed are:

a.	ϵ_{33}^{T}	=	dielectric constant for field and dielectric displacement in the 3 direction under the condition of constant stress on the body, farads/meter (F/m).
b.	ϵ_o	=	dielectric constant of free space = 8.8542×10^{-12} farads/meter (F/m).
c.	$\epsilon_{33}^{T}/\epsilon_o$	=	elative dielectric constant, free.
d.	K_{33}^{T}	=	$\epsilon_{33}^{T}/\epsilon_o$.
e.	k_{31}	=	transverse or lateral coupling factor.
f.	k_{33}	=	longitudinal or extensional coupling factor.
g.	k_{eff}	=	effective coupling and coefficient.
h.	d_{31}	=	piezoelectric constant, transverse or lateral strain/field at constant stress, meters/volt (m/V).
i.	d_{33}	=	piezoelectric constant, longitudinal strain/field at constant stress, meters/volt (m/V).
j.	g_{31}	=	piezoelectric constant, transverse or lateral strain/charge density at constant stress, volt meters/newton (Vm/N).
k.	g_{33}	=	piezoelectric constant, longitudinal strain/charge density at constant stress, volt meters/newton (Vm/N).
l.	s_{11}^{D}	=	transverse or lateral elastic compliance at constant electric field, measured when the electrical terminals are open, meter^2/newton (m^2/N).
m.	s_{33}^{D}	=	longitudinal elastic compliance at constant charge density, measured when the electrical terminals are open, meter^2/newton (m^2/N).
n.	C_c'	=	33-mode open-circuit compliance, meter/newton (m/N).
o.	C_T	=	low-frequency capacitance at 1000 Hertz, farads (F).
p.	D^T	=	(capacitance) dissipation factor (tan δ) at 1000 Hertz, low electric field
q.	O.D.	=	mean ring outside diameter, meters (m).
r.	I.D.	=	mean ring inside diameter, meters (m).
s.	τ	=	mean ring wall thickness, $\frac{\text{O.D.} - \text{I.D.}}{2}$ meters (m).
t.	D	=	mid ring diameter, where $D =$ (O.D. $- \tau$), meters (m).
u.	L	=	mean ring height, meters (m).
v.	ρ	=	ring density, kilograms/meter^3 (kg/m^3).

w. m = ring mass, kilograms (kg).
x. A = ring cross sectional area, meter^2 (m^2).

1.1.2. Frequencies

The frequencies discussed are:

a. f_{ml} = frequency of maximum admittance for lowest frequency mode.
b. f_{nl} = frequency of maximum impedance for lowest frequency mode.
- The "lowest frequency" mode is also referred to as the "hoop" mode.
- The frequencies f_{ml} and f_{nl} are typically in the 10 to 30 kilohertz range.

c. f_{m2} = frequency of maximum admittance for best coupled mode.
d. f_{n2} = frequency of maximum impedance for best coupled mode.
- The "best coupled" mode is defined as the mode for which $(f_{n2}\text{-}f_{m2})/f_{n2}$ is greatest, and is also referred to as the "longitudinal" mode.
- The frequencies f_{m2} and f_{n2} are typically in the 100 to 200 kilohertz range.

e. $Y(f_o)$ = imaginary part of admittance at f_o = 1.0 kilohertz.
$Y(F_0) = \omega C_T$
- The frequency is typically chosen in the smooth region approximately one-half way between f_{nl} and f_{m2}.

1.1.3. Subscripts

The subscripts used are:

a. b = basic value; e.g., A_b = the basic value* of the baseline ring area.
b. a = adjusted basic value; e.g., A_a = adjusted basic value of ceramic ring area.

The contractor shall use the modal decoupling resonance method (see paragraph 3.2.2.1.1) of parameter determination to determine the d_{33}, C_T, and C_c' parameters as needed to demonstrate compliance with the ring qualification set parameter requirements. The required measurements shall not be taken sooner than ten (10) days after poling. The d_{33}, C_T, C_c' parameters so determined shall be extrapolated to the one hundred (100) day values using a contractor estimated aging rate (see also paragraph 3.2.6).

3.2.2.1. Ring Parameter Determination

This section describes the determination of ring parameters for the four hundred (400) ring qualification set and the production set of ceramic rings.

3.2.2.1.1. Modal Decoupling Resonance Method

This subsection specifies the modal decoupling resonance method of ring parameter determination for the qualification set.

3.2.2.1.1.1. Government-Supplied Data

The Government-supplied data are three (3) sets of initial input parameters with sensitivity matrices that correspond to three (3) ring areas.

The initial input parameters are baseline ring parameters with estimated measured frequencies (resonance and anti-resonances) for the first transverse and longitudinal mode of the ring and the imaginary part of the admittance between the resonances.

The sensitivity matrix pair that completes the data set [one (1) set for each choice of ring area] has the form:

$$A = \begin{matrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} \end{matrix} \qquad B = \begin{matrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \\ B_{51} & B_{52} & B_{53} & B_{54} \end{matrix}$$

The three (3) data sets are for ring areas of:

a. Area_b
b. Area_b + three (3) percent
c. Area_b + (6) percent

3.2.2.1.1.1.1. Input Parameters and Sensitivity Matrices

3.2.2.1.1.1.1.1. AREA_b

The initial input parameters and sensitivity matrix pair that corresponds to the baseline area is:

a. $s^D_{11b} = 10.97 \times 10^{-12}\ \text{m}^2/\text{N}$

b. $s^D_{33b} = 8.216 \times 10^{-12}\ \text{m}^2/\text{N}$

c. $g_{31b} = 11.46 \times 10^{-3}\ \text{Vm/N}$

d. $g_{33b} = 25.7 \times 25.7 \times 10^{-3}\ \text{Vm/N}$

e. $K^T_{33b} = 1279.2$

f. $D_b = 0.04437$ m

g. $\tau_b = 0.006371$ m

h. $L_b = 0.01095$ m

i. $\rho_b = 7504.3$ kg/m^3

j. $f_{m1b} = 23596.6$ Hertz

k. $f_{n1b} = 25226.8$ Hertz

l. $f_{m2b} = 143834.5$ Hertz

m. $f_{n2b} = 182496.5$ Hertz

n. $Y_b(fo) = 5.77306 \times 10^{-6}$ Siemens

$$A = \begin{matrix} -1.977884 & -0.001831 & 0.000050 & -0.000010 & 0.000000 \\ 0.143544 & -0.002787 & -2.253174 & -0.000780 & 0.000000 \\ -1.030001 & 0.556953 & 0.022492 & -0.015095 & -0.500029 \\ 0.146472 & 0.050013 & -1.065412 & 0.731346 & -0.500066 \\ 0.000451 & -0.000249 & 0.000037 & -0.000026 & 1.000000 \end{matrix}$$

$$B = \begin{matrix} 2.012864 & -0.036779 & 0.001603 & 0.989164 \\ -0.138496 & 0.230308 & 2.017970 & 1.055079 \\ 0.493748 & -0.494950 & 0.509029 & 0.503758 \\ -0.632005 & -0.370098 & 1.421108 & 0.459463 \\ 1.000000 & 1.000001 & -1.000401 & 0.000000 \end{matrix}$$

3.2.2.1.1.1.1.2. AREA$_b$ + three (3) percent

The initial input parameters sensitivity matrix pair that corresponds to the baseline area plus three (+3) percent is:

a. $s^D_{11b} = 10.97 \times 10^{-12}$ m^2/N

b. $s^D_{33b} = 8.216 \times 10^{-12}\ \mathrm{m^2/N}$

c. $g_{31b} = -11.46 \times 10^{-3}\ \mathrm{Vm/N}$

d. $g_{33b} = 25.7 \times 10^{-3}\ \mathrm{Vm/N}$

e. $K^T_{33b} = 1279.2$

f. $D_b = 0.0441455$ m

g. $\tau_b = 0.0065955$ m

h. $L_b = 0.01095$ m

i. $\rho_b = 7504.3\ \mathrm{kg/m^3}$

j. $f_{m1b} = 23731.0$ Hertz

k. $f_{n1b} = 25374.0$ Hertz

l. $f_{m2b} = 143283.5$ Hertz

m. $f_{n2b} = 181815.5$ Hertz

n. $Y_b(fo) = 5.94624 \times 10^{-6}$ Siemens

$$A = \begin{matrix} -1.975862 & -0.001984 & 0.000054 & -0.000011 & 0.000000 \\ 0.166561 & -0.003562 & -2.306361 & -0.001103 & 0.000000 \\ -1.029747 & 0.557179 & 0.022858 & -0.015429 & -0.500029 \\ 0.147453 & 0.044092 & -1.069532 & 0.738930 & -0.500066 \\ 0.000447 & -0.000247 & 0.000037 & -0.000026 & 1.000000 \end{matrix}$$

$$B = \begin{matrix} 2.014827 & -0.039787 & 0.001626 & 0.988151 \\ -0.161090 & 0.271753 & 2.029144 & 1.070168 \\ 0.492421 & -0.494345 & 0.509133 & 0.503449 \\ -0.631284 & -0.367330 & 1.420760 & 0.461033 \\ 1.000000 & 1.000001 & -1.000401 & 0.000000 \end{matrix}$$

3.2.2.1.1.1.1.3. $AREA_b$ + six (6) percent

The initial input parameters and sensitivity matrix pair that correspond to the baseline area plus six (+6) percent is:

a. $s_{11b}^{D} = 10.97 \times 10^{-12}$ m^2/N

b. $s_{33b}^{D} = 8.216 \times 10^{-12}$ m^2/N

c. $g_{31b} = -11.46 \times 10^{-3}$ Vm/N

d. $g_{33b} = 25.7 \times 10^{-3}$ Vm/N

e. $K_{33b}^{T} = 1279.2$

f. $D_b = 0.0439183$ m

g. $\tau_b = 0.00682272$ m

h. $L_b = 0.01095$ m

i. $\rho_b = 7504.3$ kg/m^3

j. $f_{m1b} = 23869.2$ Hertz

k. $f_{n1b} = 25526.4$ Hertz

l. $f_{m2b} = 142696.6$ Hertz

m. $f_{n2b} = 181049.9$ Hertz

n. $Y_b\ (fo) = 6.11942 \times 10^{-6}$ Siemens

$$A = \begin{matrix} -1.973707 & -0.002146 & 0.000057 & -0.000012 & 0.000000 \\ 0.197833 & -0.004585 & -2.370505 & -0.001594 & 0.000000 \\ -1.029409 & 0.557419 & 0.023173 & -0.015777 & -0.500029 \\ 0.145760 & 0.039679 & -1.070574 & 0.746719 & -0.500066 \\ 0.000443 & -0.000245 & 0.000037 & -0.000026 & 1.000000 \end{matrix}$$

$$B = \begin{matrix} 2.015843 & -0.042980 & 0.001650 & 0.987071 \\ -0.192000 & 0.323399 & 2.041039 & 1.086583 \\ 0.490937 & -0.493691 & 0.509241 & 0.503124 \\ -0.627617 & -0.367916 & 1.420424 & 0.462402 \\ 1.999999 & 1.000002 & -1.000401 & 0.000000 \end{matrix}$$

3.2.2.1.1.2. Contractor-Supplied Data

The contractor shall supply to the Government the data used in and the results of applying the modal decoupling resonance method to compute ring parameters.

All contractor-supplied data shall be in mks units.

The contractor-supplied data are:

a. Measured quantities.
b. Computed parameters.

3.2.2.1.1.2.1. Measured Quantities

When collecting the measured quantities, the contractor shall adhere rigorously to the measurement constraints detailed below.

The measured quantities are:

a. f_{m1}
b. f_{n1}
c. f_{m2}
d. f_{n2}
e. $Y(f_o)$
f. D
g. τ
h. L
i. ρ
j. m

3.2.2.1.1.2.1.1. The contractor-supplied quantities shall be measured at temperatures between twenty (20) and twenty-five (25) degrees Celsius and at a relative humidity of sixty (60) percent or less. The frequency data shall be determined no sooner than ten (10) days after polarization.

3.2.2.1.1.2.1.2. The ring shall be placed in a contractor-defined/Government-approved noninteracting fixture and f_{ml}, f_{nl}, f_{m2}, f_{n2}, and $Y(f_o)$ shall be determined.

3.2.2.1.1.2.1.3. The required frequencies and the admittance values shall be determined on a Hewlett Packard 4192A Low-Frequency Impedance Analyzer or contractor-defined/Government-approved instrumentation of equivalent or better accuracy and resolution.

3.2.2.1.1.2.1.4. The required frequencies shall be determined to a resolution of one (1.0) Hertz for the low-frequency mode (hoop resonance) and one (1.0) Hertz for the largest coupling mode (longitudinal).

3.2.2.1.1.2.1.5. The ring height shall be determined to an accuracy of one thousandth (0.001) of an inch. Measure the dimension three (3) times at points one-hundred-twenty (120) degrees apart around the ring. Then take the average of the three (3) measurements to determine L.

3.2.2.1.1.2.1.6. The ring wall thickness shall be determined to an accuracy of one-thousandth (0.001) of an inch. Measure the dimension three (3) times one hundred-twenty (120) degrees apart around the ring. Then take the average of the three (3) measurements to determine τ.

3.2.2.1.1.2.1.7. The mean diameter shall be determined to an accuracy of one thousandth (0.001) of an inch. Measure the dimension three (3) times at points approximately one-hundred-twenty (120) degrees apart. Compute the mean O.D. from the three (3) measurements and then compute D where $D = O.D. - \tau$.

3.2.2.1.1.2.1.8. The density of the rings shall be determined by the Archimedes method. The weight in water and the weight in air shall be determined to an accuracy of one-tenth (0.1) percent and the density computed as

$$\rho = \frac{w_a}{w_a - w_w} \times 10^3 \text{ kg/m}^3$$

where w_a is the weight (mass) in air and w_w is the weight in water.

3.2.2.1.1.2.2. Computed Parameters

The contractor shall use Government-supplied data, indicated by the subscript b, and measured quantities to compute ring parameters.

The contractor shall select the sensitivity matrix for the area that corresponds most closely to the (adjusted) ceramic ring area. The contractor shall compute ring parameters in four (4) steps. The four (4) steps are:

Step 1: Compute M_1, M_2, M_3, M_4, and M_5 using

$$M_1 = (f_{nl} - f_{nlb})/f_{nlb}$$

$$M_2 = \{[(f_{ml} - f_{nl})/f_{nl}] - [(f_{mlb} - f_{nlb})/f_{nlb}]\}/[(f_{mlb} - f_{nlb})/f_{nlb}]$$

$$M_3 = (f_{n2} - f_{n2b})/f_{n2b}$$

$$M_4 = \{[(f_{m2} - f_{n2})/f_{n2}] - [(f_{m2b} - f_{n2b})/f_{n2b}]\}/[(f_{m2b} - f_{n2b})/f_{n2b}]$$

$$M_5 = [Y(f_o) - Y_b(f_o)]/Y_b\,(f_o)$$

Step 2: Compute P_1, P_2, P_3, and P_4, using

$$P_1 = (D - D_b)/D_b$$

$$P_2 = (\tau - \tau_b)/\tau_b$$

$$P_3 = (L - L_b)/L_b$$

$$P_4 = (\rho - \rho_b)/\rho_b$$

Step 3: Compute P_1, P_2, P_3, and P_4, using

$$P_m = \sum_{n=1}^{5} A_{mn}M_n - \sum_{n=1}^{4} B_{mn}P_n \quad \text{for } m = 1, 2, 3, 4, 5.$$

Step 4: Compute ring parameters using

$$s_{11}^D = s_{11b}^D\,(1 + P_1)$$

$$s_{33}^D = s_{33b}^D\,(1 + P_2)$$

$$g_{31} = g_{31b}\,(1 + P_3)$$

$$g_{33} = g_{33b}\,(1 + P_4)$$

$$\epsilon_{33_T}/\epsilon_o = \epsilon^T_{33b}/\epsilon_o\,(1 + P_5)$$

$$d_{33} = \epsilon^T_{33}\,g_{33}$$

$$C_T = A\epsilon^T_{33}/L$$

$$C'_c = \frac{s^D_{33}L}{A}$$

Appendix C

DERIVATION OF THE RATIO METHOD EQUATIONS

This appendix presents the derivation of the Ratio Method equations, which are shown in the text as Eqs. (28) through (30).

First, the equation for k_{33}^2 in the text [Eq. (30)] and shown below as Eq. (C8) is taken directly from the Classical Method for obtaining the parameters of a long thin rod [C1].

The derivation of Eq. (28) in the text uses the following equation for s_{33}^D from the long thin rod:

$$s_{33}^D = \frac{1}{4\rho\ell^2 f_n^2}, \tag{C1}$$

where ρ is the density of the ceramic ring, ℓ is the length or height, and f_n is the anti-resonance frequency.

The open-circuit ceramic ring compliance, C_c' is

$$C_c' = \frac{s_{33}^D \ \ell}{A} \tag{C2}$$

where A is the area of the ceramics.

Using Eq. (C1) in Eq. (C2) gives

$$C_c' = \frac{\ell}{4\rho A\ell^2 f_n^2} = \frac{1}{4\rho A\ell f_n^2}. \tag{C3}$$

But the mass of the ring m is given by

$$m = \rho\ell A. \tag{C4}$$

Thus Eq. (C3) may be written as

$$C_c' = \frac{1}{4mf_n^2}. \tag{C5}$$

By forming the ratio $\frac{C_c'}{C_{cb}'}$,

$$\frac{C_c'}{C_{cb}'} = \left(\frac{f_{nb}^2 \ m_b}{f_n^2 \ m}\right), \tag{C6}$$

is obtained, which is the same as Eq. (28) in the text.

The derivation of Eq. (29) in the text, also shown here as

$$\frac{d_{33}}{d_{33b}} = \sqrt{\frac{C_T}{C_{Tb}}}\sqrt{\frac{C_c'}{C_{cb}}}\sqrt{\frac{K_{33}^2}{K_{33b}^2}\left[\frac{1-K_{33b}^2}{1-K_{33}^2}\right]}\,, \tag{C7}$$

where

$$K_{33}^2 = \frac{\pi}{2}\left(\frac{f_m}{f_n}\right)\tan\left[\frac{\pi}{2}\left(\frac{f_n - f_m}{f_n}\right)\right], \tag{C8}$$

begins by using

$$d_{33} = k_{33}\sqrt{\epsilon_{33}^T\, s_{33}^E}\,. \tag{C9}$$

for d_{33} taken from the Classical Method for a long thin rod. Since the free capacitance C_T is given by

$$C_T = \frac{\epsilon_{33}^T A}{\ell}\,, \tag{C10}$$

Eq. (C9) can be written in terms of the free capacitance as

$$d_{33} = k_{33}\sqrt{\frac{C_T\, s_{33}^E\, \ell}{A}}\,. \tag{C11}$$

Now one may use the following equation from the Classical Method for a long thin rod:

$$s_{33}^E = \frac{s_{33}^D}{1 - k_{33}^2}\,. \tag{C12}$$

Substituting Eq. (C12) into Eq. (C11) gives

$$d_{33} = k_{33}\sqrt{\frac{C_T\ell}{A}\,\frac{s_{33}^D}{(1 - k_{33}^2)}}\,. \tag{C13}$$

Then, substituting Eq. (C2) in Eq. (C13) gives

$$d_{33} = k_{33}\sqrt{C_T\, C_c'\,\frac{1}{(1 - k_{33}^2)}}\,. \tag{C14}$$

Finally, if the first k_{33} term in Eq. (C14) is squared and moved under the radical then

$$d_{33} = \sqrt{C_T\, C_c'\, k_{33}^2 \left[\frac{1}{(1 - k_{33}^2)}\right]} \,. \tag{C15}$$

Forming the ratio $\frac{d_{33}}{d_{33b}}$ one then obtain Eq. (C7).

REFERENCE

C1. IEEE Std 176-1978, The Institute of Electrical and Electronic Engineers, Inc., 345 East 47th Street, New York, New York 10017.

Appendix D

TR-330A PIEZOELECTRIC CERAMIC RING SPECIFICATIONS

This appendix contains the Ceramic Ring Specification, NAVSEA Dwg. No. 53711-5517076, for the AN/SQS-56 Surface Ship Sonar, TR-330A transducer. The specification is also representative of the Submarine Spherical Array, TR-317( ) sonar transducer Ceramic Ring Specification. Both FSP specifications are the same except for the material type, size of the ceramic ring, differences in baseline values, range of ceramic ring area adjustment, the number of qualification rings and qualification CSAs, and quality assurance sampling plan.

1.0. SCOPE

1.1. Scope. This specification establishes the requirements for the piezoelectric ceramic rings for the TR-330( ) transducer, including the qualification procedure for the material from which the rings are made. The allowable adjustments to meet these requirements are also specified. The symbols used in this section are defined as follows:

1.1.1. Parameters. The ceramic parameters discussed are:

PARAMETER	DESCRIPTION	UNITS
d_{33}	piezoelectric constant, longitudinal strain/field at constant stress	meters/volt (m/V)
s_{33}^D	longitudinal elastic compliance at constant charge density measured when the electrical terminals are open	meter^2/newton (m^2/N)
C_c'	33-mode open-circuit compliance	meter/newton (m/N)
C_T	free capacitance at 1000 Hertz	farads (F)
D_T	(capacitance) dissipation factor (tan δ) at 1000 Hertz, low electric field	
K_{33}^T	relative free dielectric constant	
I.D.	mean ring inside diameter	meters (m)
O.D.	mean ring outside diameter	meters (m)
L	mean ring height	meters (m)
ρ	density	kilograms/meters^3 (kg/m^3)
m	ring mass	kilograms (kg)
A	ring cross sectional area	meter^2 (m^2)

1.1.2. Frequencies. The frequencies discussed are:

a. f_m = frequency of maximum admittance for best coupled mode.

b. f_n = frequency of maximum impedance for best coupled mode.

- The "best coupled" mode is defined as the mode for which $(f_n^2 - f_m^2)/f_n^2$ is greatest, and is also referred to as "longitudinal" mode.
- The frequencies f_m and f_n are typically in the range 140 to 185 kilohertz.

1.1.3. Subscripts. The subscripts used are:

a. b = baseline value, a government-determined and government-supplied quantity; e.g., A_b = the basic value* of the baseline ring area.
b. a = adjusted basic value; e.g., A_a = adjusted basic value right area.
c. s = stack; e.g. d_{33sb} = baseline stack piezoelectric constant.

2.0. APPLICABLE DOCUMENTS

2.1. Government documents. The following documents, of the issue in effect on date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein. Whenever the referenced documents conflict with this specification, this specification shall govern.

SPECIFICATIONS:

Military

MIL-I-45208	Inspection System Requirements
MIL-P-116	Preservation, Methods of

STANDARDS:

Military

DOD-STD-1376A(SH)	Piezoelectric Ceramic for Sonar Transducers (Hydrophone and Projector)
MIL-STD-105D	Sampling Procedures and Tables for Inspection by Attributes
MIL-STD-130	Identification and Marking of U.S. Military Property

DRAWINGS

NAVSEA

53711-5517053	Ceramic Stack Assembly
53711-5517119	Test Requirements Specification

*"basic value" is the name of the first number of a two-part dimensioning number. For example in Figure 1 the ring O.D. is 2.000 ±0.010 inches. The basic value of this dimension is 2.000.

Copies of specifications, standards, and drawings required in connection with specified procurement functions should be obtained from the contracting agency or as directed by the contracting officer.

2.2. Non-Government documents. The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of the specification shall be considered a superseding requirement.

STANDARDS:

Industry

ANSI/IEEE STD 176-1978	IEEE Standard on Piezoelectricity, Institute Electrical and Electronic Engineers, Inc., 345 E. 47th Street, New York, NY 10017, 29 September 1978

Technical society and technical association specifications and standards are generally available for reference from libraries. They are also distributed among technical and using Federal agencies.

3.0. REQUIREMENTS

3.1. Ceramic characteristics.

3.1.1. Polarization. The ceramic ring shall be polarized through the axis perpendicular to the electrodes on the ends of the rings.

3.1.1.1. Polarity marking. The polarity shall be marked according to DOD-STD-1376A(SH), paragraph 5.2.2.

3.1.1.2. Silicone oil prohibition. Silicone oil shall not be used in polarization or in any other ceramic process.

3.1.2. High-field characteristics. The ceramic material shall be a Type I composition as identified in paragraph 4.1 of DOD-STD-1376A(SH).

3.1.2.1. High-field. When measured in accordance with DOD-STD-1376A(SH), paragraph 5.2.4.1.5 and Table IV, 100 days or less after polarization, the change in the relative dielectric constant K_{33}^{T} and dielectric loss factor (tan δ) of the ceramic ring, shall not exceed the requirements for Type I material.

3.1.3. Exposure tolerance. The ceramic ring shall be capable of withstanding exposure to an atmosphere of 100% relative humidity at 25 degrees Celsius for 10 days, without the dissipation factor rising above 0.010 when measured at 1.0 kilohertz ±20 Hertz.

3.1.4. Thermal stability. When measured in accordance with DOD-STD-1376A(SH), paragraph 5.2.4.1.4, the maximum allowable change in free relative dielectric constant K_{33}^T shall be 10 percent when measured 100 days or less after polarization.

3.1.5. Aging. The dielectric constant aging rate of the ceramic ring (ΔK_{33}^T% per time decade) shall NOT EXCEED −6.0%.

3.1.6. Electrodes. The electrode material shall be fired silver and shall not separate from the ceramic when tested per 4.3.9.3. The electrodes shall fully cover the lateral end surfaces of the rings; no margin at edges except for the chamfer or radius as shown on Figure 1. The perimeter of the electrode at the I.D. and O.D. of the ring shall be smooth and continuous without sharp points and irregularities. The resistance between any two points (and all points) on the electroded surface shall be less than 1 Ohm.

3.1.7. Identification. Each ceramic ring shall be identified by the vendor's code and a serial number which also provides identification of the powder batch number and poling date. Mark per MIL-STD-130 and per DOD-STD-1376A(SH) paragraph 5.2.2.

3.1.8. Physical characteristics.

3.1.8.1. Dimensions. Physical dimensions of the electroded-polarized ring shall be in accordance with Figure 1, except for the allowance in 3.2.1.2. The inside and outside surface of the ring shall be the as-fired surface except as specified in 3.1.8.1.1.

3.1.8.1.1. Surface finish. Should the contractor be unable to make as-fired rings and maintain the outside diameter and wall thickness tolerances shown in Figure 1, the dimensions can be adjusted to within tolerance by machine grinding. But, the contractor shall provide data and demonstrate to the satisfaction of the contracting agency that the ground rings will not exhibit poor corona characteristics. If the contracting agency does not approve, then all machine-ground rings shall be subjected to an individual ring corona test. Rings that exhibit corona discharges greater than 10 picocoulombs with an applied voltage of 4.5 kilovolts at any frequency between 60 and 1000 Hertz shall not be accepted.

3.1.8.2. Surface and edge irregularities. The number of open chips, pits, or edge irregularities shall not exceed three total for any ceramic element (see Figures 2 and 3 for maximum allowable dimensions). No closed chips or cracks shall be allowed (see DOD-STD-1376A(SH) Appendix B for identification of terms).

3.1.8.3. Density. The density, ρ, of the ceramic ring shall be > 7450 kg/m^3.

3.1.9. Piezoelectric parameters. At a temperature of 22.5 ¨2.5 degrees Celsius and 420 days after poling the piezoelectric parameters shall be as follows:

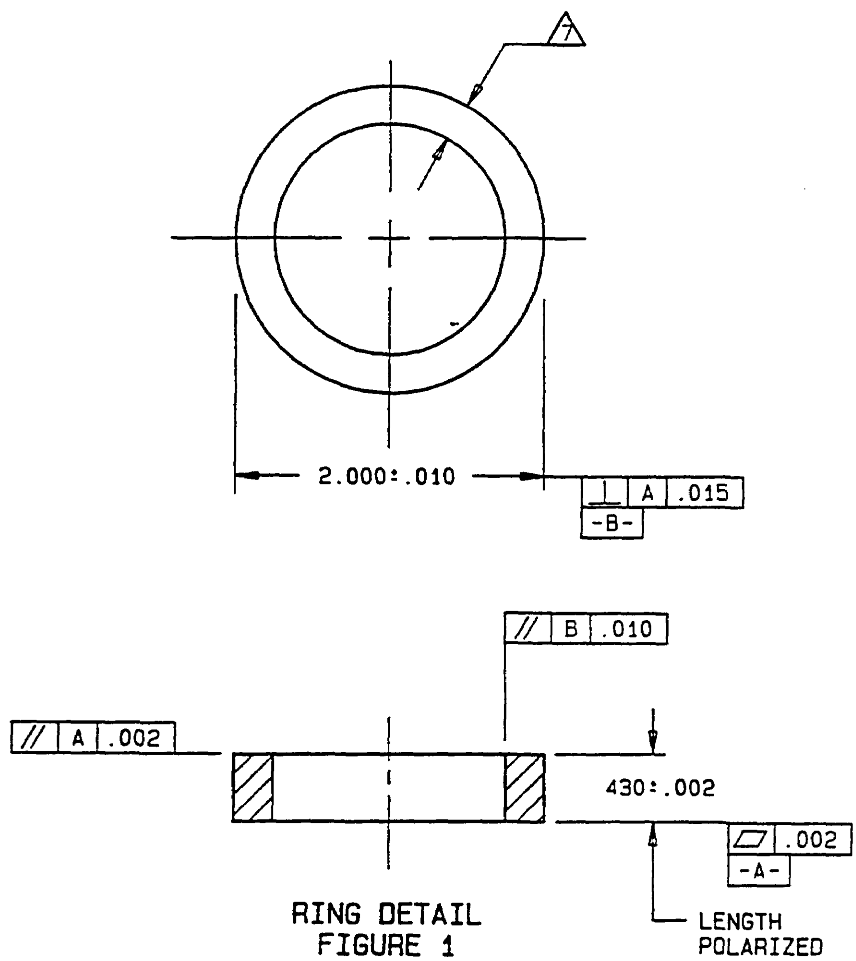
3.1.9.1. Range of parameters. The range of d_{33}, C_T, D_T, and C_c' parameters:

a. $d_{33} = d_{33b} \pm 10\%$, where $d_{33b} = 302.2 \times 10^{-12}$ m/V, 420 days after poling.

NOTES:

1. ELECTRODES SHALL BE FIRED SILVER 0.0005/0.0015 THICK.
2. ELECTRODES SHALL COVER THE LATERAL END SURFACES OF THE RING.
3. 0.020 MAXIMUM CHAMFER OR RADIUS ON CORNERS.
4. POLARIZATION SHALL BE PERPENDICULAR TO THE ELECTRODE SURFACES AND PARALLEL TO THE AXIAL LENGTH OF THE RING.
5. DIMENSIONS SHOWN ARE FOR THE ELECTRODED-POLARIZED RING.
6. INSIDE AND OUTSIDE SURFACES SHALL BE THE "AS-FIRED" SURFACE, EXCEPT AS SPECIFIED IN 3.1.8.1.1.

7△ BASELINE WALL THICKNESS IS 0.250±.010 INCHES BUT MAY BE ADJUSTED AS SPECIFIED IN PARAGRAPH 3.2.1.2 ITEM A.

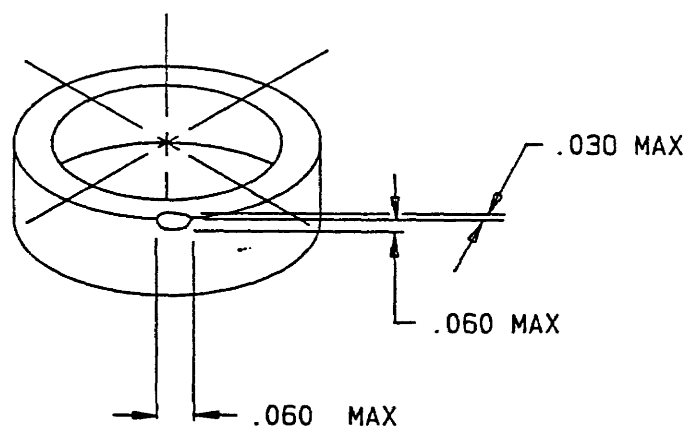


RING DETAIL
FIGURE 1

SIZE	FSCM	DWG NO.	REV
A	53711	5517076	
SCALE		SHEET 15 OF 18	

NOTES:

1. THERE SHALL BE NO MORE THAN 2 CHIPS OF MAXIMUM DIMENSION ON ANY SURFACE AND NO MORE THAN 4 CHIPS PER RING.
2. OPEN CHIPS CAN BE A SOURCE OF HIGH CORONA. CHIP AREAS SHOULD BE ABRAIDED WITH 320 GRIT OR LESS ABRASIVE TO REMOVE FEATHER EDGES OF SILVER ELECTRODE THAT MAY EXIST.
3. CHIPS LESS THAN 0.025 X 0.025 X 0.025 SHALL NOT BE CONSIDERED A CHIP.



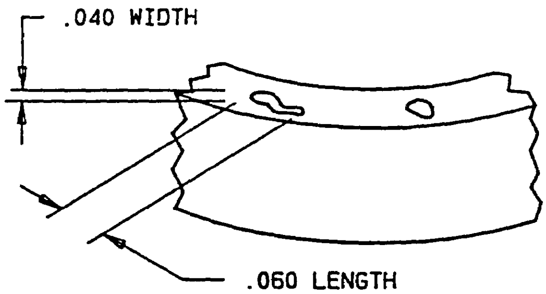
OPEN CHIP SPECIFICATION

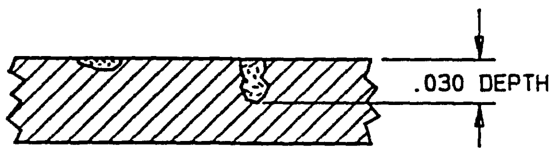
FIGURE 2

SIZE	FSCM	DWG NO.	REV
A	53711	5517076	
SCALE		SHEET 16 OF 18	

NOTES:

1. THERE SHALL BE NO MORE THAN ONE PIT UP TO THE MAXIMUM DIMENSION OF EITHER THE INSIDE OR OUTSIDE DIAMETER OF THE RING OR THE ELECTRODE SURFACE.





CROSS-SECTION
PITS

PITS
FIGURE 3

SIZE	FSCM	DWG NO.	REV
A	53711	5517076	
SCALE		SHEET 17 OF 18	

b. $C_T = C_{Tb} \pm 10\%$, $C_{Tb} = 966$ pF, 420 days after poling.

c. $D_T < 0.006$.

d. $C'_c = C'_{ca} {}^{+6\%}_{-0\%}$ (see 3.2.1.2 for definition of C'_{ca}).

3.1.9.2. Parameter mean values for 4-ring subsets. The parameter mean values for d_{33}, C_T, and C'_c for each 4-ring subset shall be:

(1) $\bar{d}_{33} = d_{33b} \pm 4\%$.

(2) $\bar{C}_T = C_{Tb} \pm 4\%$.

(3) $\bar{C}'_c = C'_{ca} \pm 3\%$.

NOTE: The 4-ring subsets are used to construct CSAs (see also 3.2.1.2d and 3.3d below).

3.2. Piezoelectric ceramic material qualification.

Unless otherwise stated references to contract or contractor made in the following sections refer to the prime transducer contract or contractor.

3.2.1. Qualification procedure.

The contractor shall perform a piezoelectric ceramic ingredients qualification phase on each piezoelectric ceramic ingredients lot as defined in 3.2.1.1. Upon successful completion of all steps of ingredients qualification phase the contractor shall change the nomenclature from piezoelectric ceramic ingredients lot to qualified piezoelectric ceramic ingredients lot. The contractor shall qualify the piezoelectric ceramic ingredients as follows:

a. Establish piezoelectric ceramic ingredients lot.

b. Fabricate and qualify a representative 400-ring set.

c. Fabricate 30 ceramic stack assemblies (CSAs) and validate in CSA dynamic tester (CDYT).

d. Iterate, if necessary.

e. Validate aging rate.

3.2.1.1. Piezoelectric ceramic ingredients lot. The contractor shall select piezoelectric ceramic ingredients, procure and store a sufficient quantity of the selected piezoelectric ceramic ingredients to produce either a minimum of 10,000 transducers or all of the transducers required by the contract; however, in no case shall the size of a piezoelectric ceramic ingredients lot exceed that reasonably required to complete the contract. If additional ingredients are used in a subsequent iteration of the qualification procedure (see 3.2.1.5), the contractor shall add such ingredients to the piezoelectric ceramic ingredients lot. In the event that no single lot of raw material is sufficient to produce the required quantity of transducers, then multiple lots must be blended to produce a homogeneous qualification lot from which rings must be made, and of sufficient size to produce a minimum of 10,000 transducers or the number of transducers required by contract.

3.2.1.2. Ring qualification set. The contractor shall fabricate, from the piezoelectric ceramic ingredients lot, a representative 400-ring qualification set. The contractor shall ensure that all of the rings in the ring qualification set meet the requirements of 3.1. Additional requirements for the ring qualification set are as follows:

a. The one time adjustable basic values are restricted as follows:

(1) $A_a = A_b \begin{smallmatrix}+6\%\\-0\%\end{smallmatrix}$, where $A_b = 8.8674 \times 10^{-4}$ m^2.

(2) $(I.D.)_a$ adjusted as needed to achieve A_a.

(3) $C'_{ca} = C'_{cb} \begin{smallmatrix}+8\%\\-4\%\end{smallmatrix}$, where $C'_{cb} = 10.11 \times 10^{-11}$ m/N.

b. The contractor shall adjust and control all ring ingredients and all ceramic ring fabrication processes in such a manner that each specified ring parameter value and characteristic is met.

c. The contractor shall determine the ring qualification set, ring parameters, and characteristics (see 4.3).

d. The ring qualification set shall be formed and maintained as ring subsets of 4 rings each using a d_{33} and C_T ring selection procedure. Each 4-ring subset shall meet the requirements of 3.1.9.2.

The contractor shall have the option to achieve $\bar{C}_T$ (as given above) by means of a one-time area adjustment as specified above in a.(1), if such adjustment is necessary.

3.2.1.3. Build and test 30 CSAs. The contractor shall fabricate and test 30 CSAs per Dwg. No. 53711-5517053 using 4-ring subsets from a 400-ring qualification set which has met all the requirements of 3.2.1.2. The 30 CSAs shall meet all the requirements of Dwg. No. 53711-5517119, Section 3.2, Ceramic Stack Assembly (CSA) Dynamic Test. Within 30 days after the successful completion of the CSA Dynamic Test the contractor shall select, at random, 10 CSAs from the 30 CSAs tested and deliver them, along with all the test data and computations on the 30 CSAs, to the contracting agency.

3.2.1.4. Iterations. If the 30 CSAs meet the requirements of 3.2.1.3, the ingredients lot becomes the qualified piezoelectric ceramic ingredients lot. If the 30 CSAs do not meet the requirements of 3.2.1.3, iterate 3.2.1.1 through 3.2.1.3 until the requirements are met.

3.2.1.5. Validate aging rate. The contractor shall set aside 80 rings of the qualification ring set, and shall test these rings to verify:

a. That ring aging rate meets ring aging rate requirements of 3.1.5.

b. The contractor-estimated aging rate used to compute the 420 day estimated values for d_{33}, C_T, and C_c' are valid (see 4.3.4.2).

3.3. Approved ring production set. The contractor shall fabricate, from the qualified piezoelectric ceramic ingredients lot (see 3.2) an approved ring production set (ARPS). The ARPS shall consist of 4-ring subsets. The rings used to form the ARPS shall meet the individual ring requirements of 3.1. Additional requirements for the ARPS are as follows:

a. The adjusted basic values A_a, $(\text{I.D.})_a$, and $C_{ca}' = s_{33}^D \, L/A$ shall be fixed, for the life of the qualified piezoelectric ingredients lot, equal to the corresponding mean values of the successful 400-ring qualification set.

b. The contractor shall control and use the qualified piezoelectric ceramic ingredients lot and all ceramic ring fabrication processes in such a manner that each specified ring parameter value and characteristic is met.

c. The ARPS shall be formed and maintained as 4-ring subsets using a d_{33} and C_T ring selection procedure; for each subset the mean value of d_{33}, C_T, and C_c' shall meet the requirements of 3.1.9.2. The formation and maintenance of the 4-ring subsets shall be accomplished either by physical segregation into 4-ring subsets or through application of a contractor specified, contracting agency approved, inventory system.

d. An ARPS shall contain a minimum of either: (1) five hundred 4-ring subsets, or (2) enough 4-ring subsets to complete the contract. However, in no case shall the size of the ARPS exceed that reasonably required to complete the contract.

e. A separate ARPS containing sufficient 4-ring subsets for the First Article transducer construction is allowed. The ARPS for First Article transducer construction shall consist of 4-ring subsets in proportion to the piezoelectric ingredients sublot size.

The contractor shall ensure that no production stacks are fabricated until after establishment of an ARPS that meets all requirements. The contractor shall ensure that all the ceramic rings used in production transducers are supplied from the ARPS. As 4-ring subsets are used from the ARPS, the contractor shall produce additional 4-ring subsets such that a qualified ARPS exists at all times.

4.0. QUALITY ASSURANCE PROVISIONS

4.1. General. The contractor/supplier shall provide and maintain an effective inspection system in accordance with MIL-I-45208.

4.1.1. Responsibility. Unless otherwise specified in the contract or purchase order, the contractor/supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the contracting agency. The contracting agency reserves the right to perform any of the inspections set forth in the specification or other test and/or inspections where such tests or inspections are deemed necessary to assure that the supplies and services conform to the requirements.

4.1.2. Test data recording. The contractor/supplier shall develop and maintain test data; documenting the results of all tests specified herein (and all tests performed by the supplier). The test documentation shall state the calculated test results and include all data from which the results were calculated. Furthermore, the documentation shall fully identify the samples by vendor, lot number and serial number, as appropriate.

4.2. Classification of inspection. Applicable inspections are classified as follows:

a. Qualification Inspections

b. Quality Conformance Inspections

4.2.1. Qualification inspection. Inspections shall be performed on ceramic rings and CSAs produced with equipment and procedures normally used in production. Samples shall be tested and inspection completed prior to regular production. Inspection of the 30 CSAs in 3.2.1.3 shall be in accordance with Dwg. No. 53711-5517053 and Dwg. No. 53711-5517119 section 3.2, Ceramic Stack Assembly Dynamic Test. A piezoelectric ceramic ingredients lot is considered qualified if all of the requirements of 3.2 are met. Table 1 identifies the test requirements of the Qualification Inspection for the individual ceramic rings of the ring qualification set. Requalification shall be required anytime 12 months have elapsed since previous manufacture has occurred by a given supplier or anytime the qualified ingredients lot (see 3.2.1.1) is depleted.

4.2.2. Quality conformance inspection. Quality conformance inspection shall include production inspection and production control inspection.

4.2.2.1. Production inspection. Production inspection shall be performed on 100% of the ceramic rings produced and shall consist of the inspections specified in Table 1.

4.2.2.1.1. Production lot. A production lot is defined as maximum of 1,000 ceramic rings fabricated by the same personnel, processes, and fabricated from the Qualified Piezoelectric Ingredients Lot.

TABLE I. CROSS-REFERENCE OF REQUIREMENTS TO QUALITY ASSURANCE PROVISIONS FOR CERAMIC RINGS

REQUIREMENT	REQUIREMENT PARAGRAPH	Q.A. PROVISIONS PARAGRAPH	LEVEL OF INSPECTION PER MIL-STD-105		
			RING QUALIFICATION PARAGRAPH	PRODUCTION ACCEPTANCE	PRODUCTION CONTROL
IDENTIFICATION	3.1.7	4.3.1			
POLARIZATION	3.1.1	4.3.3	100 PERCENT INSPECTION	100 PERCENT INSPECTION	
PHYSICAL CHARACTERISTICS (Dimensions & Surface)	3.1.8	4.3.2			NOT APPLICABLE
PIEZOELECTRIC CERAMIC PARAMETERS Range of Ring Parameters	3.1.9.1	4.3.4.1 & 4.3.4.2			
4-Ring Subset Parameter Mean Values	3.1.9.2	4.3.4.3			
ELECTRODES Finish	3.1.6	4.3.9 & 4.3.9.1			
Resistance Adhesion		4.3.9.2 & 4.3.9.3	NORMAL INSPECTION LEVEL II		NORMAL INSPECTION LEVEL S-3
AGING	3.1.5 3.2.1.5	4.3.8	SINGLE SAMPLING AQL = 2.5	NOT APPLICABLE	SINGLE SAMPLING AQL = 6.5
THERMAL STABILITY EXPOSURE TOLERANCE	3.1.4 3.1.3	4.3.6 4.3.5	LOT SIZE 400 RINGS		LOT SIZE 1,000 RINGS
HIGH-FIELD	3.1.2 3.1.2.1	4.3.7			
DENSITY	3.1.8.3	4.3.10	SAME AS ABOVE	NOT APPLICABLE	NOT APPLICABLE

SIZE	FSCM	DWG NO.	REV
A	53711	5517076	
SCALE		SHEET 18 OF 18	

4.2.2.2. Production control inspection. Production control inspection shall be performed on each production lot. Inspection shall consist of the inspection tests specified in Table I performed in the order shown. Sampling and level of inspection shall be in accordance with Table 1.

4.3. Test methods.

4.3.1. Identification inspection. Markings and identification shall be visually inspected to determine compliance with the requirements of 3.1.1.1 and 3.1.7.

4.3.2. Physical characteristics, dimensions and surface inspection. Measurement of physical dimensions and visual inspection for pits, chips, and cracks shall demonstrate compliance with 3.1.8. Go and no go gauges can be established by the contractor for the measurement of physical dimensions. Compliance with 3.1.8.2 can be established by visual inspection using a part which exhibits open chips and pits of maximum acceptable dimensions: chip or pit measurement is not required.

4.3.3. Polarity test. Polarization shall be functionally inspected with an electrometer (or a voltmeter with high input impedance) connected to the electrodes to indicate the electrical charge as an external force is applied to the ceramic ring. With the positive electrode connected to the electrode marked positive, applying a compressive force to the electroded surface of the ring shall result in a positive voltage and will demonstrate compliance with 3.1.1.1.

4.3.4. Ring parameter determination. The required measurements shall be made at a temperature of 22.5 ±2.5 degrees Celsius and at a relative humidity of less than or equal to 60 percent.

4.3.4.1. Frequency (f_m and f_n), capacitance (C_T), dissipation factor (D_T), and mass (m) measurement. The frequency of maximum admittance (f_m), the frequency of maximum impedance (f_n), and the free capacitance (C_T) and dissipation factor (D_T) are direct electrical measurements. These measurements shall be made with the ceramic ring in a contracting agency-approved fixture to simulate a stress-free elastic boundary and with an electrical signal of sufficiently low amplitude as to permit free response of the piezoelectric material. C_T and D_T shall be measured at 1 kilohertz. Instrumentation suitable to measure the requirements is a Hewlett Packard 4192A Low Frequency Impedance Analyzer or equivalent. The mass (m) of the ceramic ring can be measured on any suitable scale or balance. The frequencies f_m and f_n shall be measured to an accuracy of 5.0 Hertz, C_T to an accuracy of 5.0 pF, and m to an accuracy of 0.05 grams.

4.3.4.2. Compute ring d_{33} C_c'. This section describes the computation method for determination of ring parameters d_{33} and C_c' for all ceramic rings. Ring d_{33} and C_c' parameters shall be determined from Government-supplied baseline data and from contractor-measured ring quantities. The results of the computations, along with the measured values of C_T and D_T from 4.3.4.1, extrapolated to 420-day values using a contractor-estimated aging rate (see 3.2.1.5), shall be used to determine compliance with 3.1.9.1.

4.3.4.2.1. Government-supplied baseline data. The Government-supplied baseline data corresponds to ring data measured at 22.5 ¨2.5 degrees Celsius for rings 420 days old after poling. The baseline data are applicable to all ceramic rings that meet the requirements of this drawing, including all area adjusted rings, regardless of their specific area.

4.3.4.2.1.1. Baseline data set.

a. C'_{cb} = See 3.2.1.2
b. f_{mb} =142954.7 Hertz
c. f_{nb} =182365.3 Hertz
d. m_b =0.07328 kilograms
e. C_{Tb} =(see 3.1.9.1)
f. d_{33b} =(see 3.1.9.1)

4.3.4.2.2. Contractor measured quantities. The measured quantities are:

a. f_m
b. f_n
c. C_T
d. m

4.3.4.2.3. Computations. The contractor shall use the Government-supplied baseline data and the contractor-measured quantities (4.3.4.2.2) to compute ring parameters as follows.

Determine the compliance of the ring, C'_c, using the equation

$$\frac{C'_c}{C'_{cb}} = \frac{f_{nb}^2}{f_n^2}\,\frac{m_b}{m}\,.$$

Determine d_{33} (material parameter) using the equation

$$\frac{d_{33}}{d_{33b}} = \sqrt{\frac{C_T}{C_{Tb}}\,\frac{C'_c}{C'_{cb}}\,\frac{k_{33}^2}{k_{33b}^2}\,\frac{(1-k_{33b}^2)}{(1-k_{33}^2)}}\,,$$

where

$$k_{33}^2 = \frac{\pi}{2}\,\frac{f_m}{f_n}\tan\left[\frac{\pi}{2}\left(\frac{f_n-f_m}{f_n}\right)\right].$$

4.3.4.3. Approved ring production set test. Using a contractor-developed contracting agency-approved test method, the contractor shall demonstrate compliance with 3.3.

4.3.5. Ceramic exposure tolerance measurement. The stability of the ceramic in the presence of high humidity shall be determined.

Place the ceramic ring(s) in an environmental chamber with an established atmosphere of 100% relative humidity at 25 ±2.5 degrees Celsius and maintain this condition for 10 days. Then remove the rings, sponge off excess water or dry with a paper towel and within 30 minutes determine the capacitance and dissipation factor at 1.0 kilohertz. This test can also be made by submerging the ceramic in deionized, distilled water for the required time and temperature. Then remove the rings and treat them as given above. The test results shall determine compliance with 3.1.3.

4.3.6. Ceramic thermal stability (ΔK_{33}^T) measurement. The percentage change in relative free dielectric constant (ΔK_{33}^T) shall be measured in accordance with DOD-STD-1376A(SH), paragraph 5.2.4.1.4. The measured values and the results of the required computations shall be used to determine compliance with 3.1.4.

4.3.7. Ceramic high field measurement. The characteristics of the ceramic dielectric constant (K_{33}^T) and dielectric dissipation factor (tan δ) relative to high drive shall be determined. Measurements shall be made in accordance with DOD-STD-1376A(SH), paragraph 5.2.4.1.5 and Table IV of the standard. The measured values and the results of the required computations shall be used to determine compliance with 3.1.2 and 3.1.2.1.

4.3.8. Ceramic ring aging measurements. The time-dependency of the ceramic ring parameters shall be measured to provide aging data that will describe the changes in transducer performance as a function of ceramic age. The free capacitance (C_T) and the frequencies f_m and f_n, and the mass shall be measured as given in 4.3.4. The first set of measurements shall be made within the period 7 to 14 days after poling; the second set 30 to 45 days after poling; and the third set 70 to 100 days after poling. The measured values and the results of computations shall be used to demonstrate compliance with 3.1.5 and the aging requirements in 3.2.1.5.

4.3.9. Electrode inspection.

4.3.9.1. Electrode finish. Visual inspection, without magnification, of electrodes and electrode perimeters shall determine compliance with 3.1.6.

4.3.9.2. Electrode resistance. Electrode resistance may be measured by a bench volt-ohmmeter and test probes. Test results shall determine compliance with the resistance requirements of 3.1.6.

4.3.9.3. Electrode, adhesion. Electrode adhesion shall be inspected by the test described in DOD-STD-1376A(SH), paragraph 5.2.4.1.8 (Adhesive Tape Pull Test) except that the tape shall be applied radially, overlapping the I.D. and O.D. of the ring. No loss of electrode from the ceramic greater than 1% of the area covered by the tape shall occur. Test results shall determine compliance with the adhesion requirements of 3.1.6. A suitable tape for this test is 3M brand No.894-2T4, or equivalent.

4.3.10. Density measurement. The density shall be measured in accordance with DOD-STD-1376A(SH) paragraph 5.1.4.1.2. Results shall demonstrate conformance with 3.1.8.3.

5.0. PREPARATION FOR DELIVERY

5.1. Packaging. The ceramic rings shall be shipped in accordance with MIL-P-116, Method III.

5.2. Handling. After poling, the ceramic ring shall not be subjected to temperatures higher than 60 degrees Celsius. Adequate precautions shall be taken by the supplier to insure that these temperature limits shall not be exceeded during shipment to the procurement activity's facility.

6.0. NOTES

6.1 Intended use. Ceramic rings manufactured to this specification shall be used as the electroacoustic sensor for a sonar transducer.

6.2. Ordering data. Procurement documents shall specify the title, drawing number, and revision of this specification.

6.3. Suggested source(s) of supply. Identification of the suggested source(s) of supply hereon is not to be construed as a guarantee of present or continued availability as a source of supply for the item(s).

VENDORS	FSCM
Channel Industries, Inc. 839 Ward Drive P.O. Box 3680 Santa Barbara, CA 93105	12407
EDO Corporation 2645 South 300 West Salt Lake City, UT 84115	24338
General Electric Company Electronics Park (Bldg 3) Syracuse, NY 13221	13688
Honeywell, Inc. 5121 Winnetka Ave., N New Hope, MN 55428	64027
Vernitron Piezoelectric Division 232 Forbes Road Bedford, OH 44146	06961
Almax Industries Ltd. 61 Needham St. Lindsay Ontario, Canada K9V-4Z7	36715

Appendix E

TR-317R CSA SAMPLE PRODUCTION BUYS

TR-317R CSA SAMPLE PRODUCTION BUYS

This appendix describes the objectives, scope, and results of two independent competitive contracts called TR-317R CSA Sample Buy Contracts. Although focused on the TR-317R transducer element, these Sample Buy contracts contributed to the general STRIP solution of the k_{33} mode ceramic ring reproducibility problem.

Two CSA Sample Production Buys

From the beginning, part of the STRIP plan had been to use some form of Sample Production Buys to help perfect the TR-317R [later called the TR-317()] Fabrication Specification Package (FSP). In particular two such contracts were issued in May 1986 to address the piezoelectric ceramic portions of the FSP, one contract to Raytheon Corp. and one to Westinghouse Corp. The Raytheon contract was completed in the last part of 1987, and the Westinghouse contract was approximately 85% complete when it was terminated in the third quarter of FY87 because of funding limitations.

Objectives and Scope of CSA Contracts

Briefly stated, the objectives of these CSA Sample Buys were to develop, from a full-scale production point of view, hardware, hardware test data, and FSP corrections and/or improvement recommendations needed to complete and validate the piezoelectric ceramic portions of the TR-317R FSP.

A more complete understanding of these objectives and the scope of the CSA Sample Production Buys can be obtained from the following reprint of the CSA Sample Buy contract statement of work.

Statement of Work
Ceramic Stack Assembly Sample Production Buys

BACKGROUND

The Navy Sonar Transducer Reliability Improvement Program (STRIP) has developed a first iteration TR-317R Fabrication Specification Package (FSP). Certain portions of the FSP need to be exercised in a sample production buy in order to complete and validate the FSP.

The Ceramic Stack Assembly (CSA) portions (see the Parts List of Dwg. No. 53711-5516938) of the FSP are addressed by the herein defined sample production buy. CSAs have been constructed using earlier versions of the FSP and these CSAs met the performance requirements of the FSP. However, tolerance values and other requirements in the CSA portions of the FSP are, in some cases, based on a very limited data set.

The CSA portions of the FSP emphasize not only the CSA drawing (Dwg. No. 53711-5516938) but also the Piezoelectric Ceramic Ring (PCR) specification control drawing (Dwg. No. 53711-5516940) and the CSA Dynamic Test found as Sec. 3.2 in the Test Requirement Specification (Dwg. No. 53711-5517023, Sec. 3.2).

OBJECTIVE

The objective of the contract is to use a sample CSA buy to develop from a full-scale production point of view hardware, hardware test data, and FSP correction and/or improvement recommendations needed to complete and validate the CSA portions of the TR-317R FSP.

APPROACH

A prime contractor-subcontractor team (hence forth called the "contractor team") is required (see for example Task 2). A sample production buy of CSAs will be used to provide the contractor team with the "hands-on" hardware and testing experience needed to achieve the contract objective. Since the sample production buy cannot be large enough to simulate full-scale production, the prime contractor is required to have full-scale sonar transducer production and testing experience, resources and capabilities, and thus the ability to extrapolate results from the sample production buy to a full-scale production point of view. In particular the contractually required recommendations for FSP improvements and/or corrections must be developed to apply to a full-scale production application of the FSP.

TASK REQUIREMENTS

In performing the tasks defined below the contractor team shall attempt to meet the relevant FSP performance requirements. However, one purpose of the contract is to determine from a full-scale production point of view whether the performance requirement tolerances are practical and realistic. Therefore, provisions are made in the following tasks for possible Government-approved contractor-recommended changes in the FSP (at least for purposes of the herein defined sample production buy) including possible changes in the performance requirement tolerances. Any mistakes discovered in the FSP will be the subject of corrective action by the Government. All Government-approved contractor-recommended changes to the FSP which would affect the herein defined contract would only become part of the contract if the changes could be made within the total price of the contract.

In general the construction and testing (including test result documentation) in the tasks defined below shall be in accordance with the FSP. However, the FSP is written for a full-scale production contract and thus contains certain requirements, such as the number of units for first article construction and testing, which are not applicable to the construction and testing portion of the herein defined sample production buy. The FSP, modifications listed below apply only to the sample buy construction and testing; the contractor is required to consider the unmodified FSP when developing, from a full-scale production point of view, the FSP correction and/or improvement recommendations. These FSP modifications for the purpose of construction and testing in the tasks defined below are as follows:

M1. Drawing No. 53711-5516938 - No modifications except to subsidiary drawings as indicated below.

M2.9 Drawing No. 53711-5516940 - Modified as follows:

M2.1 Item 3.2-b - Change "one thousand (1000)" to "one hundred (100)" ring set.

M2.2 Item 3.2-c - Change "thirty (30)" to "six (6)." Thus item 3.2-c would read as follows: Fabricate six (6) Ceramic Stack Assemblies (CSAs) and validate in CSA dynamic tester (CDYT).

M2.3 Item 3.2-e - ET testing - delete

M2.4 Item 3.2.1 - Interpret "transducers" to mean "CSAs." Thus item 3.2.1 would read in part as follows: ...ten thousand (10,000) CSAs or...

M2.5 Item 3.2.2 - Change "one thousand (1000)" to "one hundred (100)." Thus item 3.2.2 would read in part as follows: ..., a representative one hundred (100) ring qualification set.

M2.6 Item 3.2.3 - Change "thirty (30)" to "six (6)" and "one thousand (1000)" to "one hundred (100)." Thus item 3.2.3 would read as follows: The contractor shall fabricate and test, as specified in Dwg. No. 53711-5516938, six (6) CSAs using rings from the qualified one hundred (100) ring set.

M2.7 Item 3.2.4 - Change "thirty (30)" to "six (6)". Thus item 3.2.4 would read in part as follows: If the six (6) CSAs of Section 3.2.3 meet...

M2.8 Item 3.2.5 - Test CSAs in ETs-delete

M2.9 Item 3.2.6 - Change "one hundred (100)" to "twenty (20)." Thus item 3.2.6 would read in part as follows: The contractor shall set aside twenty (20) rings...

M2.10 Item 3.3-a - Change "one thousand (1000)" to "one hundred (100)." Thus item 3.3-a would read in part as follows: The adjusted basic values...equal to the corresponding mean values of the successful one hundred (100) ring qualification set.

M2.11 Item 4.1.2.2 - Change to read as follows:

This test shall be made on:

- Ten (10) rings of the Ring Qualification Set (paragraph 3.2.2)
- Ten (10) rings from each new powder batch introduced to the production line

M2.12 Item 4.1.3.2 - Change to read as follows:

- Ten (10) rings of the Ring Qualification Set (paragraph 3.2.2)
- Ten (10) rings from each new powder batch introduced to the production line

M2.13 Item 4.1.4.2 - Change to read as follows:

- Twenty (20) rings of the Ring Qualification Set (paragraph 3.2)
- Ten (10) rings from each new powder lot introduced to the production line

M3.14 Item 5.0 - [Suggested Source(s) of Supply] - delete

M3. Drawing No. 53711-557023 - Section 3.2 - Modified as follows:

Replace all of Subsection 3.2.2 (applicability) with the following:

The CSA Dynamic Test shall be applied to all CSAs produced in the CSA sample buy contract.

The specifically required tasks are as follows:

Task 1 Test Government Furnished PCRs and CSAs

1.1 The contractor shall exercise Dwg. Nos. 53711-5516938, 53711-5516940, 53711-5517023 and all other applicable FSP documents to retest ten (10) Government Furnished PCRs and six (6) Government furnished CSAs and compare the results to the Government furnished test data for these PCRs and CSAs. The Government will also furnish six (6) CSA dynamic testers (CDYTs) and an assortment of fiberglass tuning rings for use in performing CSA dynamic tests. The contractor shall immediately notify the Government if good agreement between contractor and Government test results is not obtained. The contractor shall take the necessary steps in order to achieve agreement.

Task 2 Initiate Piezoelectric Ceramic Material Qualification

2.1 Basic Requirement: The prime contractor working with the PCR suppliers shall exercise Dwg. No. 53711-5516940 and all other applicable FSP documents to initiate the Piezoelectric Ceramic Material (PCM) Qualification Procedure. Two different PCR suppliers shall be used. The prime contractor may serve as one of the two PCR suppliers but at least one other PCR subcontractor must be used. For the purposes of Task 5 (Review and decision point 1) Task 2 shall be considered complete once the prime contractor has formally established a set of subtasks with each of the two PCR suppliers such that the role of each PCR suppliers is clearly defined and each supplier has started to perform their part of the PCM Qualification Procedure.

As indicated in M2 above (for the sample CSA buy only) the ring qualification set shall be at least 100 rings instead of the 1000 rings specified in Dwg. No. 5516940. Each PCR supplier shall produce a 100 ring qualification set. For each PCR supplier the size of the stockpiled ceramic ingredients lot shall be sufficient to produce forty (40) satisfactory CSAs as well as the those rings necessary to establish the ring qualification set.

Option 1: Same as 2.1 except for each PCR supplier the size of the stockpiled ceramic ingredients lot shall be sufficient to produce seventy (70) satisfactory CSAs.

Task 3 Procure CSA Parts (except ceramic rings)

3.1 Basic Requirement: The contractor shall exercise Dwg. No. 53711-5516938 and all other applicable FSP documents to procure all parts other than ceramic rings which are required to build all forty-two (42) CSAs to be constructed as part of the contract.

3.2 Option 1: Same as 3.1 except parts for a total of seventy-two (72) CSAs are to be procured.

Task 4 FSP Mark-Up 1

4.1 The prime contractor shall produce a modified FSP, called "FSP Mark-up 1," which incorporates all contractor-recommended FSP changes resulting from performing Tasks 1 through 3. FSP Mark-Up 1 shall be a marked-up and annotated version of the Government furnished FSP. At least seven working days before the beginning of the review of Subtask 5.1 a copy of FSP Mark-Up 1 plus the test results (documented as required by the FSP) from Tasks 1 shall be delivered to each of the following three Government representatives:

Representative 1:

Superintendent
Naval Research Laboratory
Underwater Sound Reference Detachment
Code:
Orlando, FL 32856
Attention:
Tel.

Representative 2:

Commander
Naval Ocean Systems Center
Code:
San Diego, CA 92152-5000
Attention:
Tel.

Representative 3:

Commander
Naval Weapons Support Center
Code:
Crane, IN 47522
Attention:
Building 2530
Tel.

Task 5 Review and Decision Point 1

5.1 Approximately seven working days after the contractor delivers FSP Mark-Up 1 plus the test results for Task 1, the contractor team shall participate at the contractor's facility with STRIP representatives in a review of the progress, data and any FSP correction and/or improvement recommendations resulting from performance of Tasks 1 through 4. The review shall include a discussion of specifics concerning problems and solutions to problems in establishing an effective working relation between the prime contractor and each of the two PCR subcontractors.

If the test results of Task 1 are satisfactory with possible Government-approved contractor-recommended changes in the FSP then the contractor shall proceed to Task 5.2; if not the contractor shall take the steps necessary to achieve satisfactory results.

5.2 The prime contractor shall produce a modified FSP, called the "Mod 1 FSP," which incorporates all Government-approved Contractor-recommended changes as determined during Subtask 5.1. The Mod 1 FSP shall be in the form of a marked-up and annotated version of the Government-furnished FSP. A copy of the Mod 1 FSP shall be submitted to each of the three Government representatives listed in Task 4.

Task 6 Completion of the Ring Qualification Sets

6.1 The prime contractor working with the two PCR subcontractors shall produce (iterating if necessary) two Ring Qualification sets (one from each PCR subcontractor) which meet the Mod 1 FSP requirements.

Task 7 Completion of PCM Qualification Procedure

7.1 The prime contractor shall complete the PCM Qualification Procedure by fabricating and testing, as specified in Dwg. No. 53711-5516938 of the Mod-1 FSP, six (6) (see M2 above) CSAs using rings from one PCR contractor's ring qualification set and six CSAs using rings from the other PCR contractor's ring qualification set. If the CSAs fabricated from a given ring qualification set fail to meet Mod-1 FSP requirements the contractor team is required to iterate the PCM Qualification Procedure at least twice if necessary to attempt to complete the PCM Qualification Procedure for a given PCR contractor.

Note that the prime contractor is not required to test CSAs in test bed experimental transducers (see M2 above) but instead must submit the satisfactory CSAs to the Government (see Task 9).

Task 8 FSP Mark-Up 2

8.1 The prime contractor shall produce a modified FSP, called "FSP Mark-Up 2" which incorporates all contractor-recommended FSP changes resulting from performing Tasks 1 through 7. FSP Mark-Up 2 shall be a marked up and annotated version of the Government-furnished FSP. At least seven working days before the beginning of the review of Subtask 9.1 a copy of FSP Mark-Up 2 plus the test results (documented as requited by the FSP) from Task 7 shall be delivered to the three Government representative listed in Task 4.

Task 9 Review and Decision Point 2

9.1 The contractor team shall participate at the contractor's facility with STRIP representatives in a review of the progress, data and any FSP correction and/or improvement recommendations resulting from performance of Tasks 1 through 8. A contractor-recommended documentation format for use in Task 12 shall also be reviewed.

If the test results of the Task 7 are satisfactory with possible Government-approved contractor-recommended changes in the FSP, then the contractor shall proceed to Task 9.2; if not, the contractor shall take the necessary steps to achieve satisfactory results.

9.2 The prime contractor shall produce a modified FSP, called the "Mod 2 FSP," which incorporates all Government-approved contractor-recommended changes as determined in Subtask 9.1. The Mod 2 FSP shall be a marked-up and annotated version of the Government-furnished FSP. A copy of the Mod 2 FSP shall be submitted to each of the three Government representatives listed in Task 4. In addition the CSAs constructed and tested in Task 7 shall be sent to Government representative 2 listed in Task 4.

Task 10 Approved Ring Production Sets

10.1 Basic Requirement: The contractor team shall exercise Dwg. No. 53711 5516940 of the Mod 2 FSP and all other applicable Mod 2 FSP documents to construct and test an Approved Ring Production Set (ARPS) containing four hundred (400) rings produced by one PCR contractor using that PCR contractor's qualified piezoelectric ceramic ingredients lot and a second ARPS containing four hundred (400) rings produced by the second PCR contractor using the second PCR contractor's qualified piezoelectric ceramic ingredients lot.

10.2 Option 1: Same as 10.1 except that each ARPS shall contain seven hundred PCRs.

10.3 Immediately after completion of the testing of all PCRs for the two (2) ARPS (800 rings for the Basic Requirement or 1400 rings if Option 1 is evoked) the prime contractor shall select the PCRs for use in Task 11 and ship the remainder of the PCRs (Note: the PCRs must be identified and shipped in 10-ring subsets suitable for constructing CSAs) and the corresponding test results to government representative 1 (listed in Task 4) for retesting and evaluation. The contractor shall participate in the resolution of any discrepancies between contractor and Government test results.

Task 11 Construct and Test CSAs

11.1 Basic Requirement: The prime contractor shall use ten ring PCR subsets produced in Task 10 and exercise Dwg. No. 53711-5516938 of the Mod 2 FSP and all other applicable Mod 2 FSP documents to construct and test thirty (30) CSAs which meet the Mod 2 FSP requirements. As nearly as possible depending on ARPS test results there shall be a half and half split in which fifteen (15) of the thirty (30) CSAs shall be constructed using ten (10) ring subsets form one ARPS and the other fifteen (15) CSAs using ten (10) ring subsets from the second ARPS.

11.2 Option 1: Same as 11.1 except that all the numbers relating to CSAs shall be doubled thus resulting in the construction and testing of sixty (60) CSAs.

Task 12. Deliverables

12.1 The contractor shall document the test data generated as a result of performing Tasks 1 through 11, document the recommendations for correcting and/or improving the FSP, and document corresponding arguments supporting the recommended changes. The contractor shall use a contractor-recommended Government-approved format for the total documentation package. The documentation package shall include documentation as required by the FSP for all portions of the FSP exercised in performing Tasks 1 through 11. The documentation of the recommendations for correction and/or improving the FSP shall be in the form of a modified FSP, called the "Mod 3 FSP." The Mod 3 FSP shall be a marked-up and annotated version of the Government-furnished FSP. The contractor shall submit all documentation plus all hardware produced in the contract (and not previously submitted) to the Government for acceptance. The hardware shall be submitted to Government representative 2 listed in Task 4. One full set of documentation shall be submitted to each of the three Government representatives listed in Task 4.

Task 13. Acceptance Test Review

13.1.The contractor shall participate in the resolution of any discrepancies between contractor and Government acceptance test results for the hardware submitted to the Government.

Task 14. Corrective Action

14.1 The contractor shall correct any hardware and/or hardware test deficiencies for the hardware produced in Tasks 10 and 11 which does not meet the requirements of the Mod 2 FSP or a Government-approved contractor-recommended modification of the Mod 2 FSP. The contractor shall update the Mod 3 FSP based on the hardware and/or hardware test corrective action results and experience.

NARRATIVE OVERVIEW OF SAMPLE BUY RESULTS

This section is a narrative overview of the results of the CSA Sample Buys. It is assumed that the reader is now familiar with the CSA Sample Buy statement of work given above. The detailed FSP-related corrections and recommendations resulting from the two CSA Sample Buys are found in Refs. E1 to E6.

Task 1. Test Government-Furnished Piezoelectric Ceramic Rings and CSAs

The purpose of task 1 was to verify that the contractors and the STRIP team were able to obtain the same results for the measurements required to apply the STRIP solution to the CSA reproducibility problem. This task proved so important and useful that it was recommended that a similar task be included in actual full-scale transducer production contracts.

Task 2. Initiate Piezoelectric Ceramic Material Qualification

The statement of work required that each CSA Sample Buy contract use two piezoelectric ring subcontractors. This requirement was to ensure that a subcontractor who was inexperienced in making the original baseline rings would be included; this in turn would help achieve the objective of validating the new ceramic ring specification. Both contractors chose the same two piezoelectric ceramic ring subcontractors, namely, EDO and ALMAX Industries. Because EDO is the supplier of the baseline ceramic rings, no problem was expected for EDO to deliver rings that met the specifications. EDO was also expected to be able to provide many useful suggestions for improving the piezoelectric ceramic ring specification.

ALMAX had never before attempted to produce the specified ceramic rings. Therefore, the ultimate success of ALMAX provided additional confidence that the new ceramic ring specification could be successfully used in large-scale competitive procurements. Westinghouse, apart from their contractual obligations, negotiated a preliminary three-iteration effort to help ensure that ALMAX succeeded. Westinghouse and ALMAX shared the results of this preliminary three-iteration effort with STRIP.

In each of the three preliminary iterations, ALMAX fabricated and tested 20 ceramic rings and Westinghouse fabricated and tested one 10-ring CSA from each set of 20 ceramic rings. The first set of 20 ceramic rings was machined to size (instead of as-fired) because ALMAX had to determine the shrink factor for these rings. The first set of 20 rings had a low capacitance and low d_{33} value.

Based on knowledge gained from the first set of 20 rings, ALMAX fabricated and tested a second-iteration set of 20 as-fired ceramic rings. The second set of 20 rings met the specifications requirements. The CSA using 10 of these second-iteration rings also met the CSA specification requirements. In particular the required tuning ring thickness was 0.312 inches, which is very similar to the thickness required for baseline CSAs.

A third-iteration set of 20 rings was fabricated from a different set of ingredients. These third-iteration rings provided a back-up data set in the event that the second-iteration rings did not meet specifications. The data from the third-iteration set of rings would have been used to help determine how to adjust the ingredients. Since the second iteration was successful, the third-iteration data were not required.

ALMAX was informed of the STRIP observations concerning the early aging of ceramic rings, namely, d_{33} ages about the same as C_T, g_{33} and f_n seem to stabilize early, and f_m continues to age. ALMAX was able to make measurements beginning as soon as 24 hours after poling. ALMAX found that this characteristic held from the beginning of the aging curves. ALMAX also found during their adjustments of the ceramic ring parameters that there appears to be a tendency for g_{33} and d_{33} to move in opposite direction as the ring fabrication process is altered. For example, if a given change in the process raises d_{33} then g_{33} will tend to be lowered.

Task 3. Procure CSA Parts (except ceramic rings)

This was a straightforward task, but it led to certain corrections and recommendations for the FSP.

Task 4. FSP Mark-Up 1

Task 4 (FSP Mark Up-1) was completed by both contractors. There were extensive suggested revisions to the corresponding parts of the FSP. These suggested revisions are too extensive to report in detail (see Ref. E1). For example, the CSA ring specification was extensively revised; however, no fundamental technical changes were made. The revisions primarily added to the clarity of the specification.

Raytheon, because of its extensive experience in producing TR-317 transducers, was able to make many useful and practical suggestions even at this early stage. Westinghouse also made useful suggestions and made many more as they proceeded with the sample buy contract.

Task 5. Review and Decision Point 1

At the end of the third quarter FY86, a meeting for Task 5 (Review and Decision Point 1) was held at Westinghouse, Annapolis (Maryland) followed by a meeting at Raytheon, Portsmouth (Rhode Island) to discuss the CSA sample buy. Following this meeting, many changes were made to the FSP for the two CSA contracts. The most significant change was to rearrange the Ceramic Specification (Dwg. No. 53711-5516940). This change was recommended by both Westinghouse, Annapolis and Raytheon, Portsmouth to clarify the testing procedures during the qualification phase. This change was incorporated as Mod 1 to the FSP for use in the sample buys.

EDO did not attend review 1, but Westinghouse initiated a make-up review conducted at the EDO Western facility. It was important to have EDO Western sympathetic or even enthusiastic, if possible, concerning the new 33-mode ceramic ring specification and procurement approach represented by the FSP. This goal was achieved. EDO appreciated the fact that the new approach solved an important problem that EDO, among others, had encountered. The old 31 ring specification approach had the same problem, namely, rings could meet the ring specification requirements and still not reproduce the corresponding CSA performance or meet the CSA specification requirements. The overwhelming evidence that the new 33 ring specification approach solves this problem was presented to EDO. EDO subsequently demonstrated for themselves that this was in fact the case.

Task 6. Completion of the Ring Qualification Set

Task 6 (Completion of the Ring Qualification Set) was completed by both prime contractors, Raytheon and Westinghouse. Each prime contractor received and tested a 100-ring qualification set from EDO and a set from ALMAX. All rings met all dynamic ring parameter requirements. However, some rings from both qualification sets exceeded the 4% limit on change in capacitance vs a high-field drive and the 12% limit on change of capacitance vs temperature. Both prime contractors recommended that the temperature-change limit be raised to 14%. It was also recommended that STRIP fully evaluate CSAs in the experimental transducer test devices as soon as possible after CSAs were made available via Task 9. Special attention was recommended concerning linearity and high drive requirements.

Task 7. Completion of PCM Qualification Procedure

Task 7 [Completion of PCM (piezoelectric ceramic material) Qualification Procedure] was completed by both prime contractors, Raytheon and Westinghouse. All 24 CSAs that were tested, whether constructed by using EDO or ALMAX rings, have met the CSA dynamic test requirements (recall that each of the two prime contractors must construct six CSAs by using EDO rings and six by using ALMAX rings). However, there was a tendency for the Almax CSAs to have a d_{33_s} on the low side of the allowable value. This was later traced to a problem with part of the Government-supplied data used with the RM (Ratio Method) for determining d_{33_s} (see the Task 9 discussion below).

Task 8. FSP Mark-Up 2

By the first week of January 1987, both prime contractors had completed Task 8 (FSP Mark-Up 2). Mark-Up versions of the various CSA-related drawings were submitted during the last week of December 1986; documentation of test results from completion of Task 6 and Task 7 was submitted the first week in January 1987. These documented test results included the verification of the d_{33}, C_T and S_{33}^E ring parameter aging rates and CSA dynamic test results.

It was again emphasized that experience has shown that it is difficult to establish a practical procedure for testing ceramic rings relative to the crack, chip, and pit requirements of the specification. The team explored the possibility of adopting the solution worked out by Raytheon and EDO. Instead of measuring the cracks, chips, and pits, a plaque containing examples of the maximum allowable cracks, chips, and pits is used in making pass/fail judgments for a given ring.

It was observed that strict interpretation of the Approved Ring Production Set (ARPS) requirements would require that the ARPS be formed and maintained permanently as physically segregated 10-ring subsets. It was further observed that such an interpretation would seriously limit the intended value of the ARPS, namely, a means to force all contractors to bid on a common basis relative to intelligent application of their state-of-the-art in controlling ring parameters during large-scale production. The inability to break up 10-ring subsets and recombine them into other 10-ring subsets prevents the manufacturer from taking advantage of the range parameters in the population. This problem was solved by adding a sentence similar to:

> "The formation and maintenance of the 10-ring subsets shall be accomplished either by physical segregation into 10-ring subsets or through application of a contractor-specified, contracting-agency-approved inventory system."

As originally written, the ceramic ring specification would require the formation of a large ARPS before any CSAs could be produced, not only for production transducers but for first-article transducers. Two objections were raised, one relative to the waste if first-article transducers fail to meet specifications and a second relative to the time constraints in producing first-article transducers. The Mod 2 FSP was changed to allow a separate ARPS for first-article production.

The ceramic ring specification does not call out a specific test to prove that the required ARPS does, in fact, exist at all times. One complication in describing such a test is that a practical test could depend heavily on the specific method used by the contractor to form and maintain the ARPS as 10-ring subsets. Consideration was given to adding a test requirement to section 4 of the ring specification to read as follows.

> "Compliance with all ARPS requirements (all parts of Section 3.3) shall be verified by application of a contractor-developed, contracting-agency-approved test."

The ceramic ring specification essentially forces the prime contractor to use only one ceramic ring vendor. Some members of the STRIP/contractor team think this could be dangerous in certain situations. If desired, the ring specification could be re-worded to allow two ceramic ring vendors but with little added cost in producing the transducers. For example, there could be a 50-50 split in the ingredients lot, qualification set, or ARPS.

In developing the FSP, it was originally intended that the tuning ring selected for the dynamic tester would typically be the best choice for use in the transducer as well. Production line efficiency could be of potential benefit if, on the average, the same tuning ring were needed for both applications. As specified in the CSA dynamic test, this original goal was not achieved because the original data were developed without cementing either the TMA or the fiberglass tuning ring to the CSAs when used in the actual experimental transducers (there was a shortage of parts at the time). The goal could be easily achieved by developing a new data set correlating CSA dynamic test results with properly constructed composite transducer results. It was recommended that the Navy consider developing this data set and correspondingly revise the CSA dynamic test.

The STRIP team was informed that an alternate CSA assembly process might be requested. In this process the tail mass assembly (TMA) would be cemented to the CSA before the fiberglass wrapping is applied to complete the CSA construction. This would mean that the CSA would not be available as a separate entity for testing in the CSA dynamic tester. One solution would be to construct enough of the CSAs as separate entities to meet the sample testing requirements. After the dynamic test, these CSAs could then have TMAs applied and be used for transducer construction. One objection to such an approach is that the CSAs used for dynamic testing would not have been randomly selected from the normal production line.

An alternate solution would be to develop a new CSA dynamic tester that allows the use of the actual TMA instead of the separate mass now used. The spring and rubber of the TMA would be made to act essentially only as masses by using a reversed retainer that touches only the tail mass, not the fiberglass spring. With this arrangement, any CSA/TMA assembly could be randomly selected for dynamic testing. The desirability of developing this alternate CSA dynamic tester is considered further as part of the Task 9.

Task 9. Review and Decision Point 2

The required review meetings for Task 9 (Review and Decision Point 2) were held the week of 5 January 1987. Most of the topics and results had been correctly anticipated and discussed in connection with prior tasks. However, one very important topic was not anticipated, namely, an apparent serious problem concerning the ratio method for determining d_{33}. The problem was later solved with a positive outcome. The problem and its resolution are described next.

One of the ceramic ring vendors, ALMAX, had found it possible to control the O.D. and I.D. of the ceramic rings in such a way as to not violate the ring drawing based on baseline dimensions and yet to increase the ring area ~3%. This led in turn to one prime contractor (Westinghouse) calculating d_{33} two different ways, one way by using the Government-supplied data for baseline ceramic ring area and a second way by using the Government-supplied data for a ceramic ring area 3% larger than baseline. The second calculation yielded a d_{33} that was ~1.5% higher than was given by the first calculation. The contractor thus decided to evoke the 3% area increase option because this made it easier to achieve the d_{33} requirements. However, the above observation seemed to indicate a serious problem concerning the RM for determining d_{33}. For example, suppose the RM were actually introducing errors of up to 2% based only on which Government-furnished data were chosen. Then what justification would there be for requiring that the average value of d_{33} for the 10-ring subsets be within ¨2% of the specified baseline value?

As reported in the text (subsection Robustness of the Ratio Method), the Navy studied the problem by exercising the MDRM (Modal Decoupling Resonance Method) for determining ceramic ring parameters. It was discovered that, except for the baseline area, the government-furnished reference data for use in the RM was in error. Specifically, the government-furnished data for other than baseline area had been calculated without changing ϵ_{33}^{T} as ceramic ring area was changed. The correct procedure requires that as the area is changed ϵ_{33}^{T} must be changed in such a way as to maintain the capacitance C_T equal to the baseline value. Once the government-furnished reference data was corrected, it was found that it made very little difference which set of government-furnished data was used. In other words, the RM is very robust and gives very accurate estimates of d_{33} regardless of which set of correct ring reference data is used. In fact, it was decided that only the government-furnished data for baseline area needs to be included in the FSP ceramic ring drawing for use with the RM.

This error in the nonbaseline-area government-furnished data explained the tendency for the qualification CSAs (see the Task 7 discussion) using Almax ceramic rings to have a low but acceptable value for d_{33_s}. The second-iteration rings for the ARPS (see the Task 10 discussion) were fabricated by using the proper government-furnished data (that is, the data for the baseline area) in the RM. Thus it turned out that the second-iteration CSAs (see the Task 11 discussion below) had d_{33_s} values very close to the specified basic baseline value.

Before the problem concerning the RM was solved, it was agreed that Raytheon should use the EDO rings and the remainder of the sample buy (see Task 10, Approved Ring Production Set and Task 11, Construct and Test CSAs) as an "off spec" study to determine whether or not it is meaningful to require a ¨2% tolerance on the mean value of d_{33} for the 10-ring subsets. After the ratio method problem was solved, the original basis for the off-spec study was negated. However, it was decided to proceed with the off-spec study relative to d_{33} for the 10-ring subsets because the ceramic ring vendors have not had much experience in controlling d_{33}. It was feared that in a production contract one could end up with a large residual set of rings for which there existed no companion rings to form 10-ring subsets. If the tolerance on the mean value of d_{33} for 10-ring subsets could be relaxed, it would be easier to find companion rings to form the 10-ring subsets.

For the off-spec study, it was decided to hold the tight tolerance of C_T ($\pm 2\%$) but to change from $\pm 2\%$ to a $\pm 4\%$ tolerance on the mean value of d_{33} for each 10-ring subset. The resulting CSAs were then checked in the CSA dynamic tester to determine if the $\pm 4\%$ tolerance on 10-ring subsets correlates with CSA d_{33} results and/or is leading to a low yield of usable CSAs.

It was agreed that some statement needs to be developed and added to paragraph 3.2.1.1 of the ceramic ring drawing (Dwg. No. 5516940) to require that the ingredients of the qualified ingredients lot be stored and/or used in such a way as to constitute a repeatable process in forming blended powder batches. For example, it could be required that a given ingredient be mixed until homogeneity was assured. If such blending of all of a given ingredient were not practical one might have several barrels of a given ingredient and require that each barrel of ingredients be homogeneous and that equal amounts of the ingredient be taken from each barrel and then blended for use in forming a given blended powder batch. The contractors were expected to propose a specific solution statement for inclusion in the Mod 3 FSP.

A candidate statement for inclusion in 3.2.1.1 of the ceramic ring drawing is

> "A contractor-developed, contracting-agency-approved ingredient processing and storage procedure shall be applied to ensure that each ingredient of the ingredients lot may be used to consistently produce batches of piezoelectric powder satisfactory for fabrication of ceramic rings meeting all specified requirements."

If such a requirement is included in 3.2.1.1 some corresponding test should be included in Section 4. A candidate statement is

> "A contractor-developed, contracting-agency-approved test shall be applied to demonstrate that each ingredient of the qualified ingredients lot meets the requirements of 3.2.1.1."

Task 9 was complete with the submittal by both prime contractors of a Mod 2 FSP.

Task 10. Approved Ring Production Sets

Task 10 (Approved Ring Production Sets) was completed. All four required Approved Ring Production Sets (ARPSs) were delivered by the ceramic ring vendors to the prime contractors. ALMAX produced two sets of 400 rings each, one set for Raytheon and one set for Westinghouse. The ALMAX sets were delivered as 10-ring subsets which, according to ALMAX, met all ARPS requirements. The prime contractors confirmed that the ALMAX sets did indeed meet all ARPS dynamic requirements. However, as in the case of the qualification set, some rings failed to meet the thermal stability and high-field specifications. This also was the case for EDO rings (this point is discussed further below). EDO produced a

400-ring set for Westinghouse that was not delivered as 10-ring subsets. Westinghouse segregated this set into 10-ring subsets that met the ARPS dynamic requirements but not the high-field or thermal stability requirements. As authorized, EDO produced an off-spec 400-ring set for Raytheon. This off-spec set was bimodal in d_{33}, that is, it had one distribution of rings whose typical value for d_{33} was 4% low and another whose typical value was 2% high (the goal was to be 4% high). The capacitance met the original FSP requirements. Raytheon separated this subset into various types of 10-ring subsets that best served the purpose of the subsequent off spec study.

Because of the incorrect government-furnished data, ALMAX did not make the best choice for the one-time area adjustment. By using the corrected government-furnished data, ALMAX reported that an area 1.5% larger than baseline would have been better than the +3% actually chosen. Even though ALMAX was still able to meet all requirements, a residual of unused rings was accumulating.

This experience caused ALMAX to suggest that at least a ±1.5% area adjustment (about the one-time adjusted basic value) be allowed at the discretion of the ring vendor. If this were allowed, poling could be used to develop partners for residual rings. This suggestion was considered. The consensus was that, electro-acoustically, there should be no problem. However, without thorough testing, it was feared that unforeseen problems such as corona or radial stress-related problems might arise. It was therefore recommended that STRIP mix ALMAX rings (+3% area) and EDO rings (baseline area) to test this recommendation to allow a certain discretionary ring area adjustment about the selected basic value.

Just as in the case of ring aging, it was found that if poling is used to adjust d_{33} then g_{33} tends to remain constant and thus, capacitance is approximately proportional to d_{33} ($g_{33}\,\epsilon_{33}^T = d_{33}$, $C_T = (\epsilon_{33}^T A)/\ell$). This explains why allowing a discretionary area adjustment would make it possible to use poling to generate partners for residual rings. For example, one could increase d_{33} by more thorough poling and then the corresponding increase in ϵ_{33}^T could be countered, if desired, by decreasing the area A and thus holding capacitance constant.

During the reconsideration of the one-time area adjustment it was asked if the one-time area adjustment be for the life of the contract or just for a given qualified ingredients lot? It was decided that the one-time adjustment should be for the ingredient lot. Of course in a given instance the prime contractor could further restrict the one time adjustment to the life of the contract. Therefore, in paragraph 3.3-item a of the piezoelectric ceramic ring specification (Dwg. No. 5516940), the phrase "for the life of the contract" should be changed to the phrase "for a given qualified piezoelectric ceramic ingredients lot."

Raytheon completed Task 10 by using the EDO 400 ring off-spec set to form 10-ring subsets as required to complete the off-spec study. Specifically, Raytheon formed five 10-ring subsets each of whose mean value for d_{33} was ~4% low, five 10-ring subsets with the mean value for d_{33} ~2% high, and five 10-ring subsets whose mean value for d_{33} was approximately equal to the specified baseline value. These 15 10-ring subsets were then used in Task 11 to construct the required 15 CSAs by using EDO rings and to complete the off-spec study (see Task 11 progress which follows).

As explained above, if poling is used to adjust d_{33} then there should be a tendency for capacitance C_T to rise or fall as d_{33} is raised or lowered. Raytheon reported that this was indeed the case for the 15 off-spec 10-ring subsets. Although Raytheon was able to maintain the mean value of C_T for each 10-ring subset within $\pm 2\%$ of the baseline value, there was a strong bias for the 10-ring subsets with a lower value of d_{33} to also have a lower value of C_T and those with the higher d_{33} value to have a higher value of C_T.

Task 11. Construct and Test CSAs

Because of funding constraints, the Westinghouse contract was terminated before completion of Task 11 (which consisted of construction of CSAs using ceramic rings from the ARPS). The hardware was delivered as individual rings or partially constructed CSAs.

Raytheon completed construction of all required CSAs, 15 by using ALMAX ARPS and 15 by using EDO off-spec study rings. Since the parameters of the ALMAX 10-ring subsets were in the middle of the specified range, all properly constructed ALMAX CSAs (12 CSAs) also had parameters in the middle of the specified range for the Ceramic Stack Assembly Dynamic Test (CDYT). The three ALMAX CSAs that failed had some rings installed with reversed polarity. It was noted that the latest ALMAX CSAs tended to require a thinner fiberglass tuning ring (0.218 in.) for the CDYT than the ALMAX qualification CSAs (0.250 in.).

The five CSAs constructed by using the EDO off-spec-study rings with the low d_{33} (-4%) either failed to meet the CDYT test requirements or just barely met requirements. Specifically, the ratio f_n/f_m was either too low or almost too low. Also these five CSAs had low values of capacitance but were within the specified range. The 10 CSAs constructed by using EDO rings with midrange or higher values of parameters easily met the CDYT requirements.

Task 12. Deliverables

Westinghouse had previously delivered qualification rings and CSA hardware as follows: 69 rings (approximately half ALMAX and half EDO rings) to NRL-USRD and six EDO CSAs serial numbers (S/Ns 1 through 6) and six ALMAX CSAs (S/Ns 7 through 12) to NOSC. Because of the termination of the Westinghouse CSA Sample Buy, Westinghouse did not deliver any more completed CSAs. Westinghouse did deliver nine partially completed CSAs and 710 second-iteration rings to NWSC. These rings were approximately half EDO rings and half ALMAX rings.

Raytheon delivered to NWSC the following hardware: from the qualification phase, six CSAs made with EDO rings, six CSAs made with ALMAX rings, 20 EDO rings and 38 ALMAX rings; from the second iteration, 13 CSAs using EDO rings (Raytheon temporarily retained two CSAs made with EDO rings), 12 CSAs (two of which contained a ring with reversed polarity) made with ALMAX rings (Raytheon temporarily retained two CSAs made with ALMAX rings), 220 EDO rings and 239 ALMAX rings. An additional CSA made with ALMAX rings was destroyed in the process of showing that this CSA contained a ring with reversed polarity.

Task 13. Acceptance Test Review

Task 13 (Acceptance Test Review) was essentially waived because all relevant issues had been resolved as part of the prior tasks.

Task 14. Corrective Action

Task 14. (Corrective Action) was not required because all relevant corrective action had already been taken as part of the prior tasks.

REFERENCES

E1. R.W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) Fourth Quarter Progress Report," NRL Memorandum Report 5934, Oct. 1986, Work Unit IV.D 4b.

E2. R.W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) FY87, First Quarter Progress Report," NRL Memorandum Report 5978, Jan. 1987, Work Unit IV.D. 4b.

E3. R.W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) FY87 Second Quarter Progress Report," NRL Memorandum Report 6027, Apr. 1987, Work Unit IV.D. 4b.

E4. R.W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) FY87 Third Quarter Progress Report," NRL Memorandum Report 6068, July 1987, Work Unit IV.D. 4b.

E5. R.W. Timme, "Sonar Transducer Reliability Improvement Program (STRIP) FY87 Fourth Quarter Progress Report, NRL Memorandum Report 6128, Oct. 1987, Work Unit IV.D. 4b.

E6. R.W. Timme and J.F. Cartier, "NAVSEA Transducer Improvement Program (NTIP) FY88 First Quarter Progress Report," NRL Memorandum Report 6189, Jan. 1988, Work Unit V.A.2.